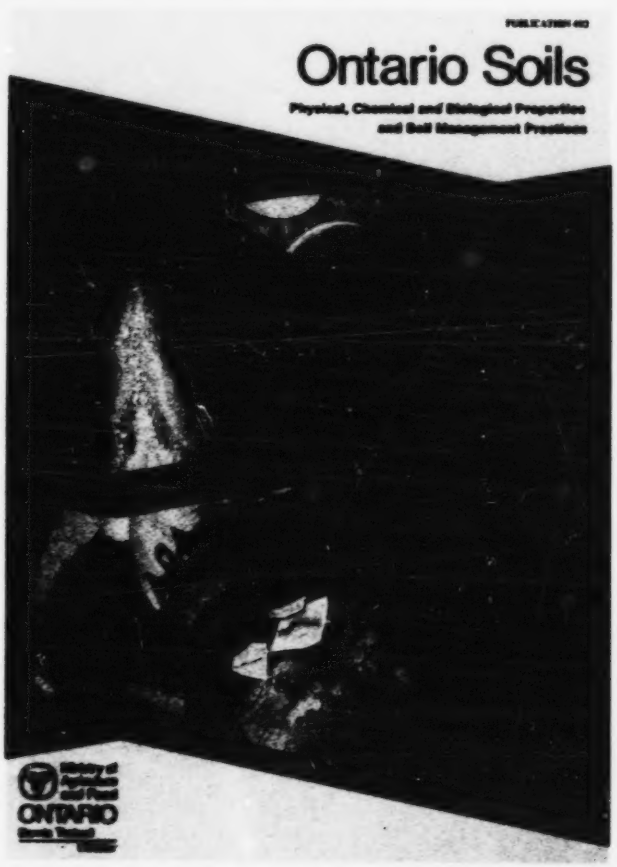
Ontario Soils

Physical, Chemical and Biological Properties and Soil Management Practices

Ministry of Agriculture and Food
ONTARIO
Dennis Timbrell
Minister

FRONT COVER

The cover shows photographs of murals which are located in the entrance hall of the Land Resource Science Building. The murals were designed and painted by Paul Buchanan, Elora, Ontario, and were the gift of Alumni and friends of the Ontario Agricultural College, University of Guelph.



ABOUT THE MURALS

IN THE BEGINNING

Red ball earth slowly cools – the harder crust shrinks and cracks – molten lava bursts through the torn surface of the earth spewing volcanic ash – continents shift – mountains push upwards – oceans explode – soil steadily accumulates – climate becomes hot and humid creating great tropical rain forests – sudden climate change – ice ages begin – oceans shrink – northern hemisphere covered by moving mass of ice grinding southward, carrying soil and rocks.

MAN AND LAND

Mankind emerges into a more stable world with regular seasons and a warmer climate – learns to cultivate soil and grow crops – earth's population increases – threat of soil resource depletion promotes scientific studies of physical realities of earth – mankind must and can work side by side with nature to create an ideal situation whereby he can live in harmony with his environment, and provide adequate sustenance for his survival.

AGDEX 500

ONTARIO SOILS

Physical, Chemical and Biological Properties

and

Soil Management Practices

BY

FACULTY AND STAFF OF THE DEPARTMENT OF LAND RESOURCE SCIENCE

L. R. WEBBER, EDITOR

ONTARIO AGRICULTURAL COLLEGE

UNIVERSITY OF GUELPH

GUELPH, ONTARIO

FOREWORD

Soil is recognized as one of our basic natural resources; it is an inheritance which provides the foundation for our life and civilization. Man obtains most of his food, clothing, and shelter from the products of the soil and the manner in which the soil is managed determines our present and future welfare.

With the world population at approximately four billion, with impending food shortages, high costs for energy, shortages of oil and natural gas, and an increasing concern for our environment, it is imperative that there be efficient management of our soils. It is within the power of the farmer to increase (or decrease) the productive capacity of his soil; what he does depends on his knowledge of soil management and on the economic pressures imposed by society. The successful farmer recognizes the importance of good soil management; his management practices are specifically designed for the soil types on his farm and for his type of farming.

The purpose of this publication is to describe the properties and characteristics of soils that are influenced by soil management and to outline the basic principles for maintaining and improving soil productivity. This publication is intended to be used by all who are vitally concerned with soil productivity and food supply.

A publication such as this requires input from many sources. It is my pleasure to acknowledge the contributions of the following personnel from the Department of Land Resource Science: T.E. Bates, E.G. Beauchamp, D.E. Elrick, D.W. Hoffman, T.J. Heeg, J. W. Ketcheson, T.H. Lane, M.H. Miller, R. Protz, R.L. Thomas, L. van Vliet, A.L. Willis. In particular, I would like to thank Professor L.R. Webber for editing this publication and acknowledge the very able assistance of D.B. Hons. I appreciate D.E. Irvine's assistance with the cartographic work.

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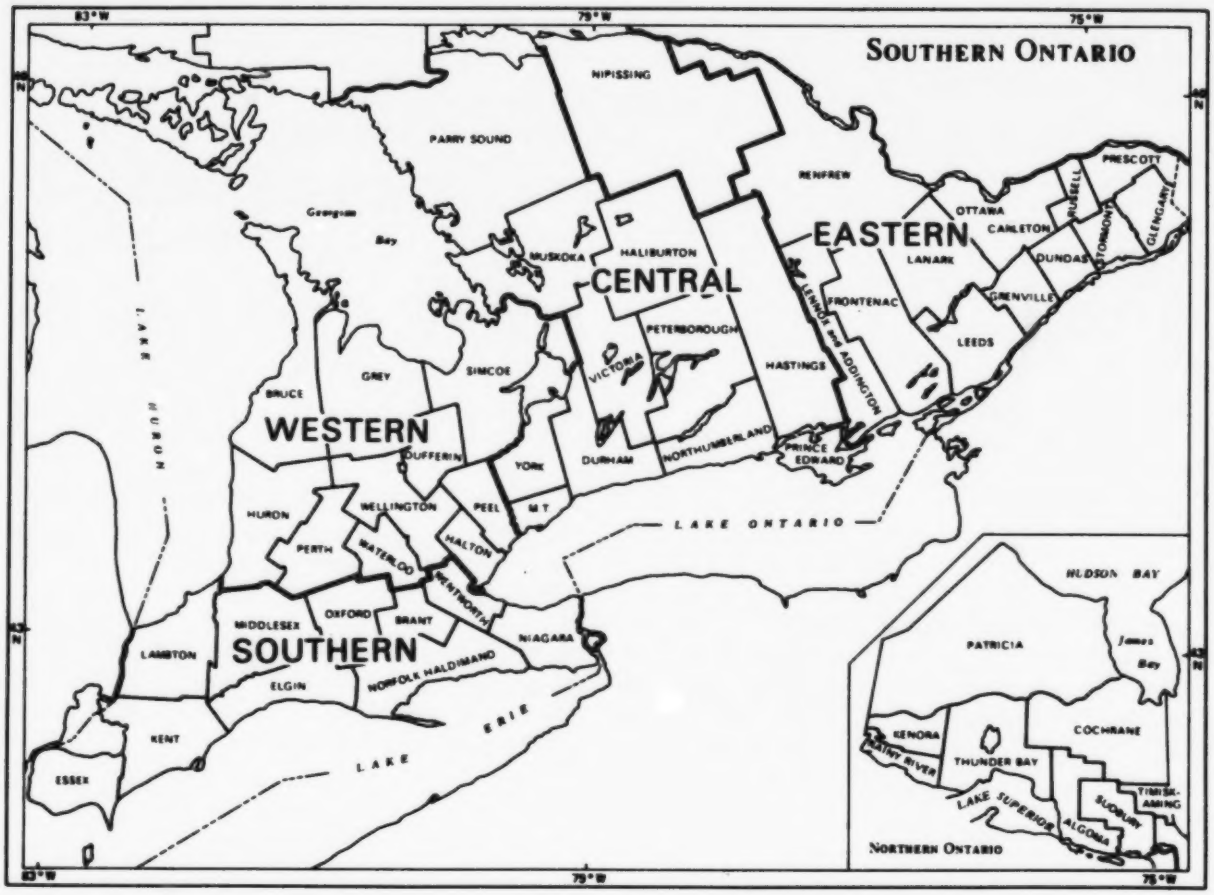

Figure 1. Counties, districts and regions of Ontario

WHAT IS A SOIL?

Soil is the natural medium for the growth of plants and furnishes the plant with an anchor for its roots as well as nutrients (including water), and oxygen for growth and reproduction.

Soils are natural products of the environment. They form in the upper-most part of the earth's crust from rocks of many kinds or from transported mixed rock debris, which may be termed alluvium (transported by water), colluvium (transported by gravity), aeolian material (transported by wind), or till (transported through the agency of moving ice). These are the parent materials of soils. A host of physical, chemical and biological processes combine to alter the original rock or rock debris; the resulting weathering and formation of soil horizons (profile development) constitute soil formation. Many of these processes are destructive and cause a breakdown of parent materials. Others are constructive and give rise to new, often complex substances that may not have been present in the original material, for example, clay minerals and humic material. Other processes lead to the localization and concentration of components of the parent material such as soluble salts, calcium in the form of carbonate (lime), and iron and aluminum in the form of their hydrated oxides. The relative intensity of individual processes, acting in concert, largely determines what kind of soil will form from a particular parent material. This intensity is controlled by environmental factors, mainly climate and vegetation, although topography and drainage exert important modifying influences. Intensity is not the only consideration. Of equal importance is the length of time that the processes have been operating, that is to say, the length of time that land surfaces have remained stable and undisturbed.

It is important to know something about climate, vegetation, geology (parent materials) and the geomorphic development of the landscape in order to understand the basic reasons why soils differ from one another and why specific soils are found at specific places. Without such understanding or "genetic awareness", soil properties and soil distribution patterns cannot be intelligently appreciated, nor can soils be seen as an integral component of the natural landscape.

Components of a Soil

All soils consist of four components:

- mineral material
- organic matter
- water
- air

Figure 2 is a diagrammatic representation of the distribution of these components in a loam soil.

The mineral materials are fragments of many kinds of rocks found in the glacial debris. This mineral fraction is often referred to as the soil skeleton of fabric (Figure 3). It is made up of particles of various sizes ranging from stones, gravel and sand, which give the soil a gritty feel, to silt and clay, which are smooth and sticky. The relative proportions of the various sized soil grains determine soil texture.

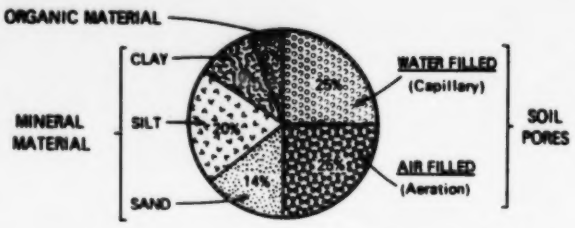

Figure 2. The volumetric composition of a loam soil when excess water has been removed. On a weight basis the percentage composition of the dry soil would be: organic matter 4%, clay 22%, silt 44% and sand 30%.

The organic fraction of a soil consists of plant roots, organisms large and small, the remains of plants and animals, and the by-products of their decay. The stable residues, humus, resulting from the decomposition of organic matter, are microscopic in size and play an important part in holding plant nutrients and water. Poorly-drained soils contain more organic material than nearby well-drained soils. The organic content of clay soils is normally greater than that of sandy soils.

Water is held within some of the pore spaces and as thin films around the mineral and organic materials. A soil retains more water as the amounts of clay and organic matter increase. Soil water contains soluble nutrients required by plants.

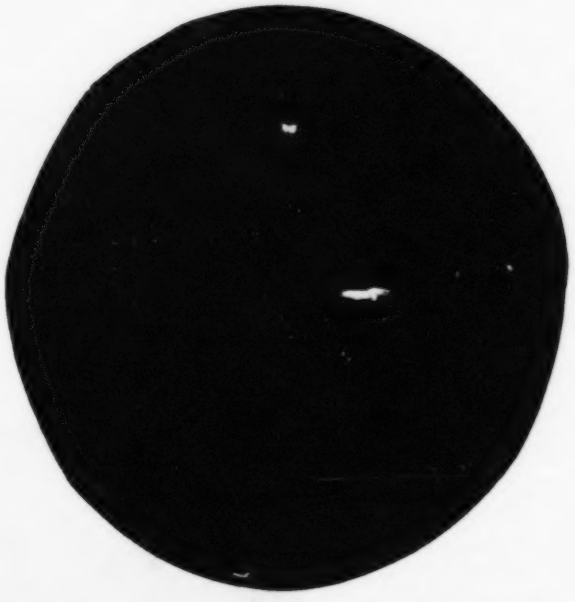

Figure 3. The variations in color, shape and size of sand grains are visible through a microscope.

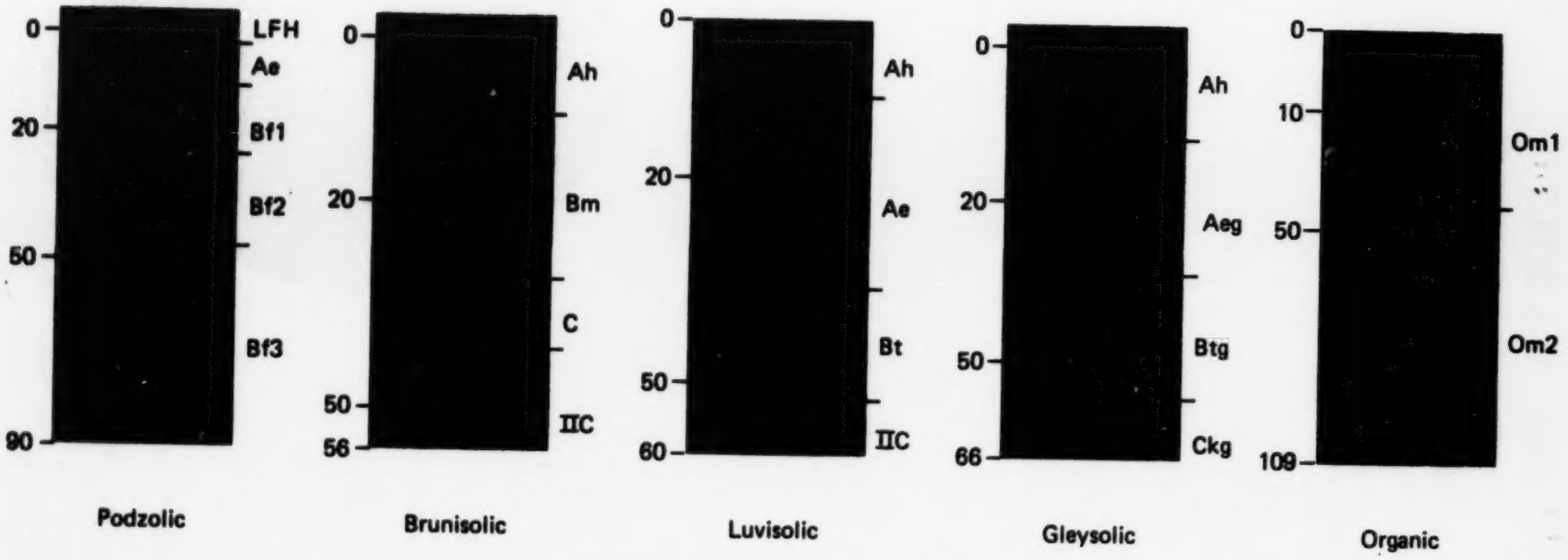

Figure 4. ***Soil profiles of five orders common to Ontario. For descriptions of the soil horizons, see the text. The depth measurements are in centimetres measured from the soil surface.***

The principal gases in the soil atmosphere are nitrogen, oxygen, and carbon dioxide. Certain soil bacteria utilize atmospheric nitrogen and produce complex organic materials. Oxygen is essential for the growth of all forms of life. Carbon dioxide combines with soil water to form carbonic acid, which assists in the release of plant nutrients from the mineral materials.

Soil Profiles

Soil is a three-dimensional medium; it has length, breadth and depth. It is impossible, in practice, to see all parts of a soil and the best that we can do is to sample it at intervals by studying restricted vertical sections known as soil profiles. When this is done in a large area such as the Province of Ontario with its diversity of climate, vegetation, rocks and landscapes, the first impression is one of continuously varying soil conditions represented by a vast and heterogeneous population of soil profiles. There exists little apparent order. No two profiles are, strictly speaking, identical although some differ in very minor respects and it is difficult to tell them apart. Others differ widely and it is easy to distinguish between them. One cannot say much that is meaningful about the population as a whole; it is far too heterogeneous. Similarly, one cannot think or talk in terms of individual profiles because they are far too numerous. To bring some order to the study of such a population, it is essential to establish classes which subdivide the range of conditions present in soils. Such classes must group like individuals together and separate them from unlike individuals and, by so doing, reduce the number of entities that needs to be comprehended. Without classification, one cannot hope to remember or manipulate the individuals or see relationships among them.

Every soil has a profile – a succession of layers from the surface down to the parent material. These layers are known as horizons and are designated by the letters A, B and C. Horizons vary in thickness from a fraction of an inch to several feet and differ from one another in color, texture, structure, reaction, and other properties. Soils are grouped into what are called orders on the basis of the kinds of major horizons present and on major differences in climate and vegetation. In Ontario representatives of five Orders occur. These are called Podzolic, Brunisolic, Luvisolic, Gleysolic and Organic.

PODZOLIC soils are well and imperfectly drained soils that have developed under coniferous and mixed-forest vegetation. These soils are usually found in cold to temperate climates on acid parent materials.

The LFH horizon is normally quite thin (1 to 3 cm) and is composed of organic materials such as tree litter (L), partially decomposed residues (F) and residues in an advanced stage of decomposition (H). The Ae horizon is a gray leached layer. The B horizon represents a layer where accumulations of iron and organic matter occur; the intensity or degree of accumulation is shown by numerals, e.g. Bfl shows greater accumulation than Bf3. The color of the B horizon is due primarily to concentrations of iron which were leached from the overlying layers. The C horizon, not shown in Figure 4, occurs beneath the B and represents the parent material of the profile. Podzolic soils are derived from materials low in bases, hence the tendency to be acidic.

BRUNISOLIC soils are well to imperfectly drained and have developed under forest conditions or tundra-like vegetation.

The Ah horizon is a mineral layer mixed with organic materials (h). The Bm layer is often said to be weakly developed in that it lacks a marked accumulation of organics or clay. The parent material, a thin C horizon, is shown in Figure 4, which is underlain by an unrelated deposit of different texture and minerology hence designated as IIC. Most parent materials are alkaline, some are acidic.

LUVISOLIC soils consist of well and imperfectly drained soils that have developed under deciduous or mixed forest covers in moderate and cool climates. The parent materials are generally neutral to alkaline in reaction.

An Ah layer is a surface horizon enriched with organic accumulations (h). Under cultivation this horizon is termed an Ap layer. The Ae is grayish brown in color due largely to the eluviation (e) of clay and organic matter. Materials leached from the A horizons tend to accumulate in the B layer; Bt indicates an accumulation of clay great enough to be significantly different from the Ae. The solum extends to the IIC horizon in the example shown in Figure 4.

GLEYSOLIC soils are saturated with water during some period of the year, unless they have been artificially drained. These drainage conditions tend to cause a profile that has varying degrees of mottling; the bright red, orange and yellow mottles are usually oxidized iron compounds.

The Ah is usually thicker than the well-drained soils. The leached horizon (Ae) is mottled due to poor internal drainage (g). The B horizon indicates an accumulation of clay (t) and is poorly drained (g). In Figure 4, the C horizon shows an accumulation of carbonates (k) as well as poor drainage (g).

ORGANIC soils are developed from accumulations of organic materials, such as grasses, reeds, rushes, sedges, mosses and trees. Organic soils vary in their stage of decomposition, a characteristic often used in their classification. These soils are saturated with water most of the year, unless artificially drained.

In Figure 4, two horizons have been identified. The Oml is a dark brown to nearly black layer of partially decomposed organic material. The Om2 layer is more brownish in color than the Oml, suggesting less decomposition of the organic residues.

Classes of Agricultural Land

In the preceding section, it was indicated that most of the soils in Ontario could be classified into one of five orders. It is possible to devise a system of classification that conveys a great deal of information about a particular soil. Such detailed information is contained in soil survey maps and reports for most counties and districts of Ontario. Soil survey information is of value to farmers, to advisors in agriculture, forestry and land use, to planners for urban development, for highway construction and recreation facilities, to engineers and many others.

Classes of land according to capability are determined by considering the characteristics of the soil profile, such as texture, structure, presence of impermeable layers, stoniness, depth to bedrock and other properties that may affect land use and have an influence on crop production. Other factors used in determining the land capability class include slope, degree of erosion, stoniness, drainage and climate. Each land class is determined by the degree or intensity of these limitations to land use. It is the soil capability classification which provides the basis for estimating the potential of soils for agriculture.

A soil capability classification for agriculture has been prepared for Ontario. The acreage of land in the various classes is found in Table 1.

Table 1. Acreages (millions) of land in various land use capability classes*

	Land Classes						
	1	2	3	4	5	6	7
Northern Ontario	-	0.8	1.8	1.3	2.1	1.2	189
Southern Ontario	4.9	4.9	3.2	1.8	1.9	2.2	9.5

Total for classes 1 to 4 for Ontario is 18.7 million acres.

**Hoffman, D. W., Soil Capability for Agriculture. Canada Land Inventory. (Generalized soil maps and capability classifications for Canada are available from Queen's Printer, Ottawa and Canadian Government Bookshops in Ottawa and Toronto).*

A summary of land use capability classes follows:

Class I Land has no significant limitations for a wide range of crops. The soils are deep, well drained and occur on level or nearly level topography. There are no serious hazards or limitations, and under good management are often the most productive soils for many farm crops.

Class II Land has moderate limitations that may restrict the range of crops which may be grown successfully. The limitations on land use are moderate and could include one or more of the following: imperfect drainage, rolling topography, moderate erosion and stoniness.

Class III Land has moderately severe limitations that restrict the range of crops or the land may require special management practices to sustain productivity. The limitations are more severe than in Class II and may affect timing and ease of tillage, planting and harvesting, as well as the range of crops that may be grown successfully.

Class IV Land is subject to severe limitations that restrict the range of crops. Generally, the soil is too susceptible to erosion, too stony or too poorly drained to be cultivated on a regular basis.

Class V The limitations are severe and normally prevent the use of land for the sustained production of annual field crops. Class V land is unsuitable for cultivation but with special intensive management (land clearing, erosion and water control) could be developed as grazing areas.

Class VI Land is capable of producing perennial forage crops and should be kept in a permanent vegetative cover. The limitations include steep slopes, severe erosion, shallow soil over bedrock or other features that make cultivation generally impractical.

Class VII Land is not considered suitable for agriculture and includes rockland, quarries and areas virtually devoid of soil.

PHYSICAL PROPERTIES OF A SOIL

Physically, a soil may be described as a porous medium consisting of finely divided organic and mineral particles, and water- and gas-filled pores (Figure 5). The amount of each component present in a soil will be important in determining the physical properties of a soil, and often has a significant effect on the suitability of a soil for plant growth (Table 2).

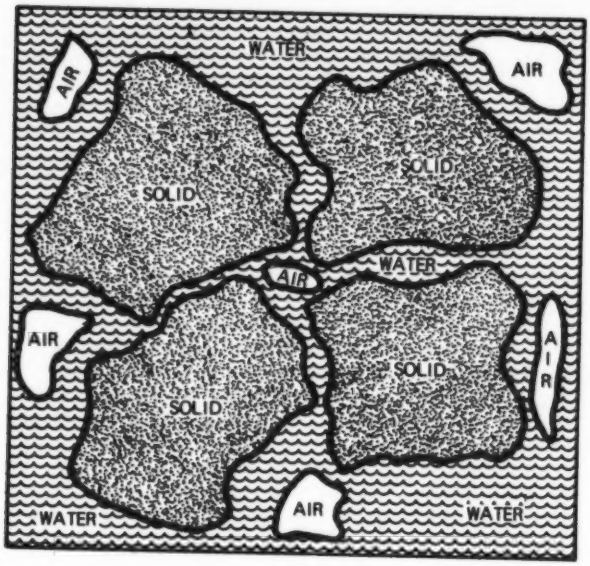

Figure 5. A soil is a three-phase system; solids (mineral and organic), water, and air.

Table 2. Some physical properties and their effects on plant growth

Soil property	Condition affected
Soil texture	– plant nutrient supply moisture content drainage workability
Soil structure	– movement of air and water size and function of pores
Soil porosity	– relative volumes of water and air root penetration

Soil Texture

The mineral particles in a surface soil, ranging in size from stones to microscopic clay particles, represent about one-half the total volume or 95% of the weight of the moisture-free sample. The proportion of the separates (sand, silt and clay) present in a soil determines soil texture. Texture is a term that describes the feel of a soil when it is wetted and rolled between the fingers – sandy soils are coarse and gritty, while clay soils are smooth and sticky.

It is obvious that the "feel of a soil" is not a sound method for determining the texture of a soil. It is necessary to determine by chemical and physical means the sand, silt and clay content of a sample of soil. The size limits of the sand, silt and clay (based on the diameter of the particle) have been established (Table 3), and knowing the percentage of any two of the separates allows the determination of the soil texture by use of a textural chart (Figures 6 and 7).

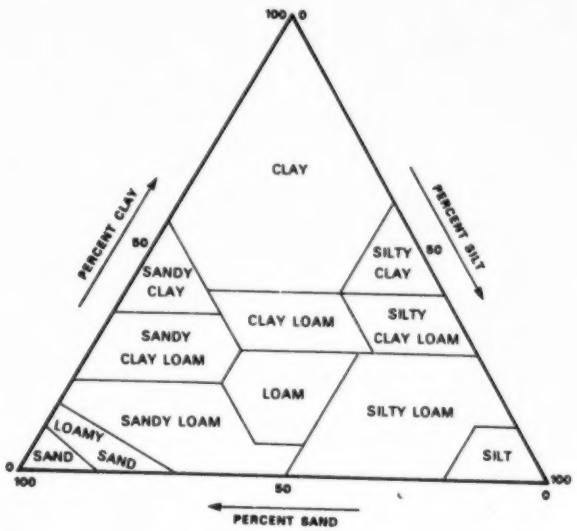

Figure 6. A diagram showing the ranges in percentages of sand, silt and clay in the soil textural classes.

Properties of the Soil Separates

Stones, gravel and sand occur in soil as single particles, often irregular or rounded in shape (Figure 3). These particles are chemically inert. The large spaces that occur between the particles facilitate the free movement of water and air. Soils with high sand or gravel contents are porous, have a low water-holding capacity but possess good drainage and aeration, and are usually friable and easily cultivated. While quartz is the dominant mineral in sands, quantities of limestone, dolomite and igneous rocks may also be present.

Silt particles are too small to be seen without the aid of a microscope. The small spaces between particles tend to retard air and water movement. Silt, silt loam, and silty clay soils have a high water-holding capacity. Various kinds of minerals occur in the size range of silt, but quartz is dominant.

In terms of the physical and chemical properties of a soil, the clay fraction is the most important. Because of the microscopic size of clay particles, a unit weight of clay has a much larger exposed surface area than does the same weight of sand or silt. The clay fraction is a storehouse for plant nutrients as well as a major contributing factor to the swelling, shrinking, stickiness and water-holding capacity of soils.

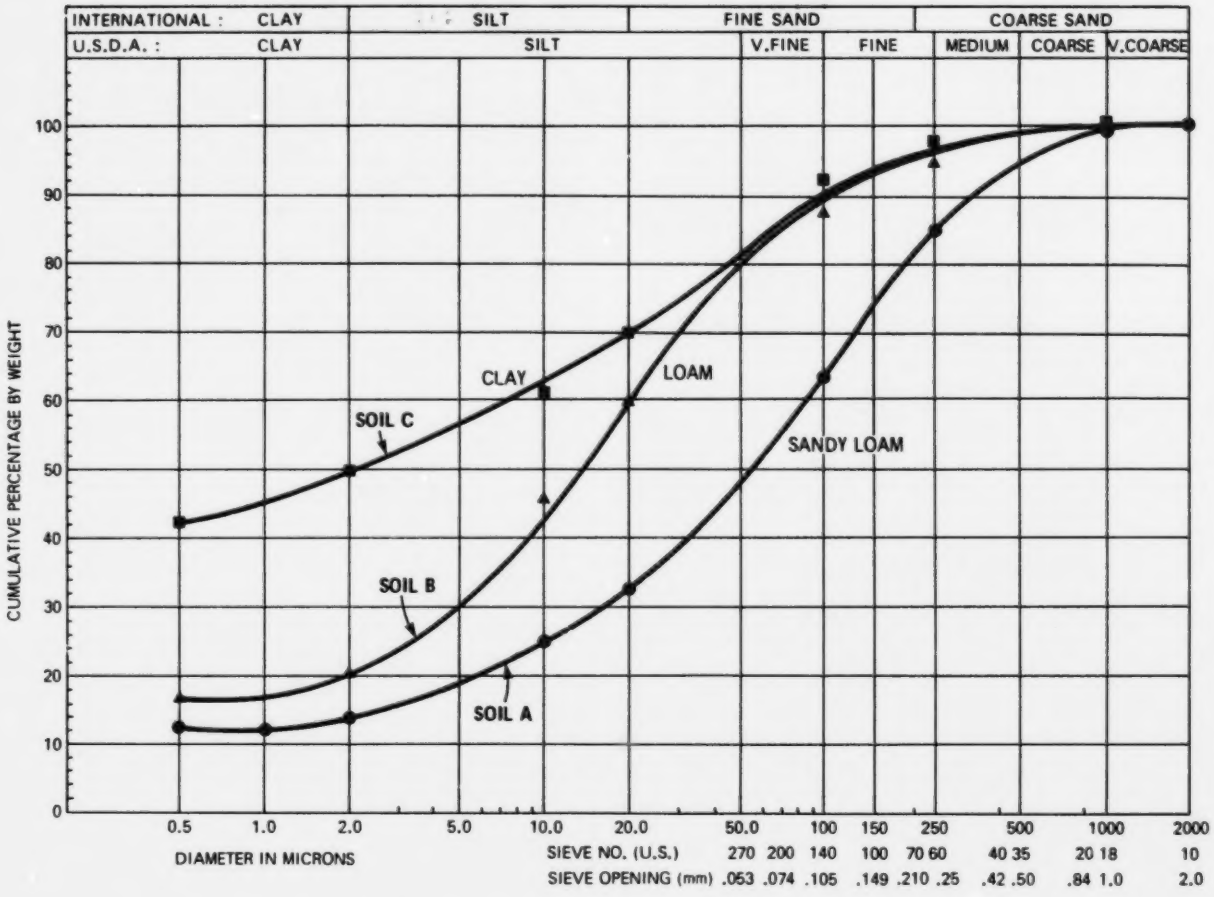

Figure 7. Particle size distribution for three soil textures.

Table 3. Particle size distribution and textural class for three soils (see also Figure 7)

Soil	Sand 2.0 to 0.05 mm* %	Silt 0.05 to 0.002 mm* %	Clay <0.002 mm* %	Textural class from Figure 6
Soil A	52	34	14	sandy loam
Soil B	20	60	20	silt loam
Soil C	18	32	50	clay

**1 inch equals 25.4 millimetres (mm)*

Rock fragments greater than 2 mm are classified according to size using such items as: gravel up to 7.5 mm, cobbles 7.5 to 25 mm, and boulders greater than 25 mm.

Soil Structure

Although texture refers to the size and amount of the mineral particles, soil structure refers to the physical arrangement of mineral and organic particles into aggregates, granules, or peds of different shapes, sizes and porosities. A desirable soil structure is composed of aggregates which are:

- water stable; do not collapse when wetted
- porous; as in the aggregates under grass crops
- variable in size, ranging from small (1.0 mm) to large aggregates (2.0 to 5.0 mm).

Types of Soil Structure

Four types in a classification of soil structure are described in Table 4.

Table 4. Description and occurrence of four common types of soil structure

Type	Description and Occurrence
Single grain	single solid particles; in sands and sandy soils that are low in clay and organic matter.
Massive	a coherent mass of soil; no definite shape; not water stable; exhibit shrinkage and swelling; in the parent materials of many clay soils.
Blocky	rectangular faces; sharp angular corners; low porosity; firm; 5 to 50 mm in size; in Bt horizons and parent materials of well-drained, fine-textured soils.
Granular	nearly spherical aggregates with rounded corners; 2 to 10 mm in size; in surface soils well supplied with organic matter and medium to fine texture.

Formation of Soil Structure

An individual soil aggregate or ped is an agglomeration of minute mineral and organic particles held together by various cementing agents, such as clay, by-products of organic matter decomposition, and iron oxide. Although a farmer is not likely to change the clay or iron oxide content of a soil, he can alter the organic matter content. Because organic matter is destroyed by biological acitivity, new organic matter must be added regularly to a soil if a good soil structure is to be maintained. The addition of easily decomposable organic material to a soil is a feature of good soil management.

Many soil organisms produce gelatinous by-products that cement soil particles into aggregates. These organisms are most active in a soil that is well supplied with organic matter and plant nutrients. Some soils require the addition of lime to adjust the soil reaction (pH) to a more favorable level for the organisms.

Crop roots and residues, especially hay and sod crops, encourage the development of a granular structure in the surface soil by the addition of organic matter and root secretions that act as cementing agents. The minute roots compress the soil particles and dehydrate the soil, an essential step in aggregate formation.

The data in Table 5 illustrate the beneficial effects of grass and organic matter on soil aggregation. In the four-year rotation, soil aggregation reaches its lowest level under corn but improves under each of the hay crops. It is doubtful if the percentages of organic matter under the crops in the rotation are significantly different except for the second-year hay.

Table 5. The effects of crop sequences on the level of soil organic matter and aggregation in a loam soil after a ten-year period

Crop Sequence*	Organic Matter (%)	Aggregation % >0.5 mm**
Continuous sod	4.4	84.7
Continuous corn	3.1	21.6
In a four-year rotation		
Corn	4.1	52.3
Oats	4.2	55.9
Hay 1st year	4.0	60.9
Hay 2nd year	4.4	74.0

** All of the crop was removed and no manure applied.*

***Aggregation is expressed as the percentage of a sample of air-dry aggregates that was water stable, and > 0.5 mm in size.*

Importance of Soil Structure

The presence of a high percentage of water-stable aggregates is desirable in fine-textured soils because it:

- increases porosity
- favors aeration
- aids in water movement in the profile
- increases the resistance to erosion by wind and water

In coarse-textured soils, the sand grains occur as separate individuals with large pore spaces around the particles. Normally, the coarse particles do not agglomerate (come together as aggregates or granules) in these soils.

Weight and Volume

To explain some basic concepts used to describe the physical properties of a soil, consider a given volume of soil as shown in Figure 5. The total volume of the sample comprises soil solids, water and air. The total weight is the weight of soil solids and water; the weight of air is neglected.

Bulk Density (B_d) describes the degree of compaction of a soil. It is expressed as grams per cubic centimetre (g/cm^3). The value is obtained when the total weight is divided by the total volume occupied by the soil sample. Under field conditions values for sandy soils are 1.4 to 1.6 g/cm^3; other soils 1.2 to 1.4 g/cm^3; and compacted soils up to 1.7 g/cm^3.

Moisture Content is determined by drying a soil to constant weight at 105°C and is expressed as a percentage or fraction of the oven dry weight of soil, e.g. 30% or 0.3 is the moisture content of a soil containing 30 lb of water for every 100 lb of oven dry soil. Moisture may be expressed as a volume if the bulk density is known, e.g. if a soil moisture content is 0.3 by weight and the bulk density is 1.3, then the moisture by volume is 0.3 (1.3) or 0.39. This is equivalent to 0.39 x 12 inches or 4.7 inches of water per foot of soil depth or 0.39 cm of water per centimetre soil depth.

Soil Porosity

In dry soil the total pore space is filled with air, and in a moist soil with water and air. In coarse-textured soils, large pores are formed by the individual sand grains, but in a fine-textured soil the volume and relative size of the pores are determined by the percentage clay and the soil structure.

Aeration and Capillary Porosities

The relative distribution of large and small pores is an important soil characteristic. This characteristic determines in part:

- need for and ease of soil drainage, either natural or artificial
- soil aeration and soil atmosphere composition
- growth and growth pattern of plant roots

The relative volumes of large pores (aeration) and small pores (capillary) may be approximated as described in the section dealing with Soil Moisture Tension.

The total porosity of clay soils that are well supplied with organic matter and are of good structure may exceed the total porosity of sandy soils, but the porosity in a clay soil would be dominated by fine capillary pores. However fine-textured soils may be compacted to such a degree that the porosity may be less than in sandy soils. Aeration porosity values serve as a criterion in judging the effects of tillage or cropping practices on soil structure (Table 6).

The determination of aeration and capillary porosities is a laboratory exercise.

Table 6. Soil porosity values and bulk densities of a loam soil under two cultural treatments

Cultural Treatment	Soil Porosity		Bulk Density
	Total	Aeration	g/cm^3
Continuous sod	53	19	1.25
Continuous corn	49	11	1.35

Soil Aeration

The atmosphere over a field is composed of nitrogen, slightly less than 79% and about 21% oxygen. Various other gases are found in very small amounts such as carbon dioxide, 0.03% or 300 parts per million. Soil aeration is primarily concerned with the maintenance of oxygen level and removal of carbon dioxide from the soil atmosphere.

The biological processes in a soil require oxygen and release carbon dioxide as a by-product. A growing plant root requires oxygen and its growth rate may be seriously limited by a deficiency of oxygen or an excess of carbon dioxide. Aeration of the soil solution containing plant nutrients is essential for adequate absorption by the roots. Under oxygen-deficient conditions, some metals (e.g iron, aluminum, manganese) change their chemical form and may reach toxic levels; sulfides and nitrites may occur in oxygen-deficient atmospheres.

The exchange of gases between the atmosphere and the soil atmosphere is accomplished by two processes: mass flow and diffusion. Mass flow refers to the movement of wind over a soil surface which is related to differences in atmospheric pressure. It is generally agreed that mass flow is a minor contributor in the exchange of gases. Diffusion refers to the movement of individual gases caused by differences in partial pressures. As the partial pressure of carbon dioxide in the soil pores exceeds the normal atmospheric value, the gas moves out of the soil. Diffusion tends to establish a uniform concentration between atmospheric gases and those gases in the soil. The diffusion rate for a soil increases with increasing soil porosity, and normally decreases as the pores fill with water or as the soil texture becomes finer.

Root penetration and proliferation are influenced primarily by gaseous diffusion, moisture content and the resistance provided by soil materials. To separate these variables and measure their effects on root growth is a complicated problem: as the soil dries out, the physical resistance to root penetration increases while gaseous diffusion may increase. Furthermore, at some point the bulk density or degree of compaction particularly in subsoils may reach values that inhibit root growth, moisture movement and gaseous diffusion. The interactions of bulk density and oxygen concentration on depth of root penetration into a compacted subsoil are shown in Figure 8. The graph indicates that root penetration is noticeably reduced when the oxygen concentration is below 10%. A relationship exists among bulk density, oxygen levels and root penetration: at a bulk density of 1.3 g/cm^3 root penetration was reduced when the oxygen level fell below 5%, but as bulk density increased the mechanical impedance became the dominant factor limiting root growth at all levels of oxygen.

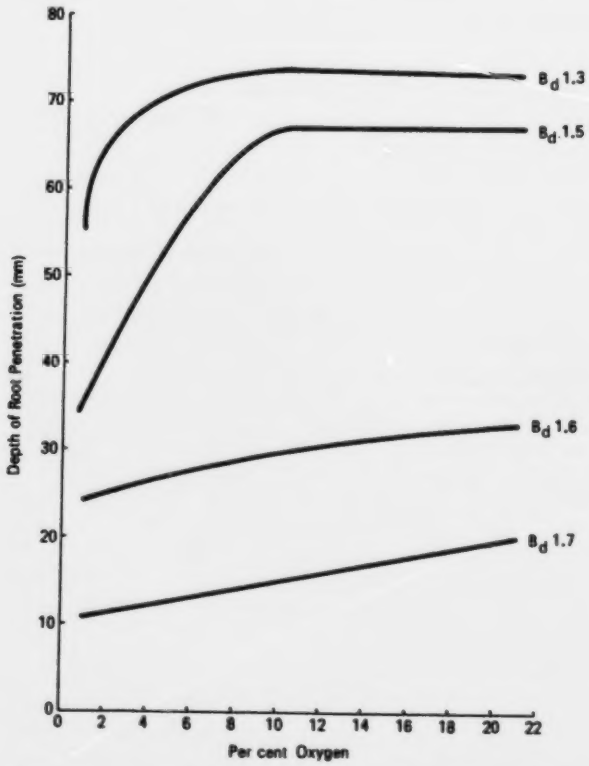

Figure 8. The effect of oxygen concentrations and bulk density on depth of root penetration into compacted subsoil.

Soil Moisture

Soil Moisture Tension

Two soils of different textures (a clay loam and a sandy loam) may have the same moisture content, but plants growing in the clay loam may wilt while plants in the sandy loam would not suffer. The marked difference in plant response is due to the energy or security with which the moisture is held by each soil. More energy must be expended to remove a small amount of moisture from the clay loam than from the sandy soil, even though both soils are at the same moisture content.

Various physical terms are used to characterize the energy with which moisture is held in a soil. A common term is "soil moisture tension" (Figure 9). When the ends of two capillary tubes are lowered into water, the water rises in the capillary tubes. The magnitude of the rise of the water is inversely proportional to the radius (r_1 and r_2 of the water column)[1]. Water is held in soil pores by physical forces similar to those holding the water in the capillaries, but soil pores are not as uniform as the capillary tube and are not

[1] *The upward force on the column of water is due to the surface tension (T) on the circumference of the capillary ($2\pi r$) or total force is $T(2\pi r)$ where $T = 72$ dynes/cm at 25°C. The opposing downward force results from the weight of water in the capillary and is equal to $d(\pi r^2 h)g$ where d = density of liquid (water = 1.0) and g the gravitational factor 980 cm/sec^2. At equilibrium the two forces are equal, hence*

$T(2\pi r) = d(\pi r^2 h)g$ from which h, the height of rise of water in a capillary of radius r cm is

$$h = \frac{2T}{rdg}$$

continuous throughout a mass of soil. The tension on the water in the capillary is equivalent to the elevation of the meniscus (water surface in the tube) above the free water table. To obtain relative values of the tension, it is customary to consider a column of water 1033 cm in height as exerting a basal pressure of one atmosphere. As the water in soil pores is above a free table, the pressure is considered to be negative which relates to the term, soil moisture tension. If soil water were under tensions equivalent to h_1 and h_2 in Figure 9, the soil at the h_2 tension would be drier than the sample at the h_1 tension.

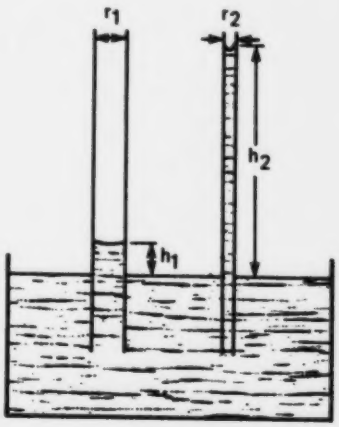

Figure 9. Capillary rise in tubes of different radii.

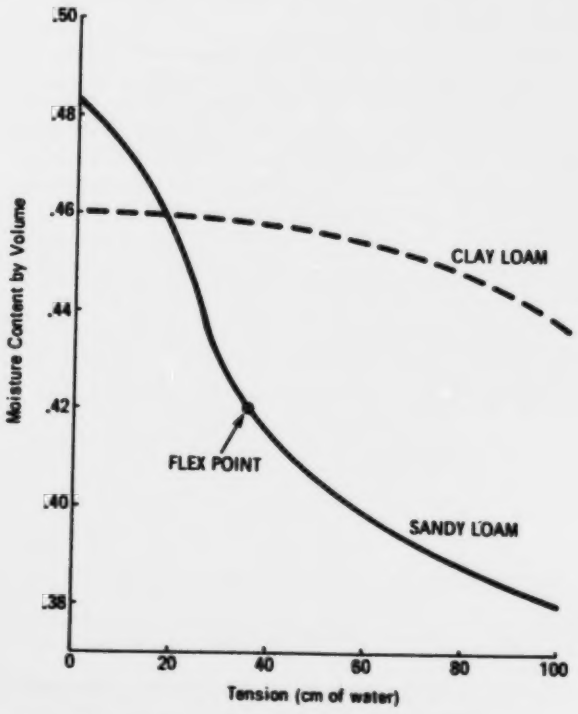

Figure 10. As the tension on soil moisture is increased, more water is removed. At a given tension the clay loam soil retains more moisture than the sandy loam.

Under field conditions a tension is exerted on the soil moisture by (1) natural drainage, (2) soil drying due to losses of water by evaporation, and (3) loss of water by plant use. Figure 10 illustrates a sequence of events as a wetted soil is allowed to drain freely. As the drainage water leaves the soil surface, relatively low tensions are developed and the large pores empty first. The water removed by normal drainage is referred to as gravitational water. As the gravitational water moves deeper into the soil, greater tensions are exerted on the water in the soil pores but eventually an equilibrium is reached between the tension and the size of pores that will drain. The volume of water retained by a soil when natural drainage has essentially stopped has been referred to as field capacity.

Field Capacity

In the preceding section, the moisture at field capacity was described as being related to the soil moisture tension that develops as a soil drains naturally under field conditions. The value is approximated in a laboratory by applying tensions equivalent to 330 cm of water or one-third bar. Field capacity is the maximum amount of water a well-drained soil can retain against gravitational forces. The moisture occurs as films around the mineral and organic particles and in capillary pores that hold the moisture against gravitational pull.

If a soil with the moisture at field capacity receives additional water by rainfall or irrigation, a layer of soil (the thickness of the layer depends on the amount of water applied) approaches a saturated condition and the drainage process starts again. In irrigating soils, enough water is added to raise 60 to 75 cm of soil (the rooting zone) to its field-capacity value. Additional water would be lost through natural drainage.

The magnitude of the moisture tension in a soil increases as the volume of small capillary pores increases; that is, a clay loam soil will develop more tension than a sandy loam. Tension increases as depth of soil increases with an upper limit in depth of 60 to 75 cm[1]. If a clay loam soil were about 30 cm in depth, it would contain more water at field capacity than if the same soil were 60 cm in depth. There are instances where a textural change occurs in a soil with depth. If a clay loam soil were underlain by coarse sand or gravel at 60 cm, the coarse materials would not exert enough tension to drain the clay loam to a normal field-capacity value. The opposite is also true in that a sandy soil underlain by a clay loam at 30 to 60 cm would contain less than normal water at field capacity due to the tensions developed in the clay loam.

Permanent Wilting Point

As a soil dries out, it becomes increasingly difficult for plants to remove water in sufficient quantities to support normal plant growth. If water is not added, the soil be-

[1] *To demonstrate the effect of length of column on drainage, thoroughly soak a bath towel. Roll the towel into a cylindrical shape, hold the roll with the long axis horizontally and allow the water to drip out. When dripping has almost stopped, allow the towel to hang with the long axis in a vertical position and observe the resumption in water loss. This experiment can be related to moisture conditions in shallow flower pots where natural drainage is not improved by a layer of stones in the bottom of the pot.*

comes so dry that the rate of moisture absorption by the roots is slower than the loss of moisture by transpiration through the leaves. At this point the plant wilts, ceases to grow, loses its rigidity and eventually dies.

The moisture content of soils at the permanent wilting point may be determined by growing plants, usually dwarf sunflowers, in pots in a greenhouse, or it may be determined in a laboratory using high pressure equipment to extract the soil moisture. It has been found that the moisture at the permanent wilting point is held by a tension equivalent to that developed by 15,000 cm of water (15 bars).

Available Moisture

Moisture retained by a soil between the tensions at field capacity and permanent wilting point may be absorbed by plants and used in their growth process.

The values for field capacity, permanent wilting point and available water for soils of different textures are shown in Table 7 and Figure 11. The field capacity and wilting point values were determined in a laboratory using pressure equipment, at one-third bar and 15 bars, respectively. The available water, as a percentage of the dry weight of soil, is the arithmetical difference between the field capacity and the wilting point values. To express the available water as a volume, it is necessary to multiply the percentage moisture by the bulk density.

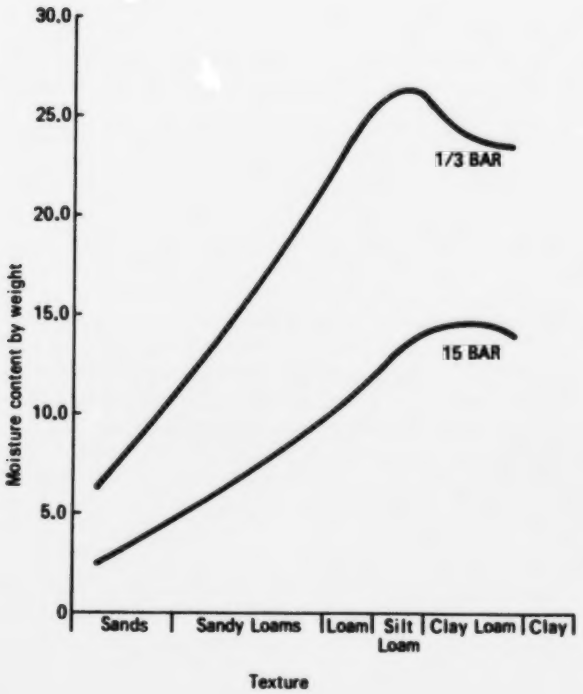

Figure 11. Plant available soil moisture increases as particle size decreases except in some clay loams and clays.

Table 7. Available water in several soils and the physical parameters that affect the moisture content

Texture	Percentage by Weight					
	O.M.	Clay	Silt	Field capacity	Permanent wilting point	Available water
Sands	1.0	3.9	8.0	6.3	2.8	3.5
	1.2	3.3	2.6	4.7	1.8	2.9
	4.1	5.1	11.4	11.1	4.2	6.9
Sandy loam	3.2	10.4	35.9	14.8	5.9	8.9
	1.8	10.3	35.8	14.8	5.1	9.7
	10.4	5.5	22.2	23.3	17.5	5.8
Loam	2.4	9.0	44.8	16.9	5.8	11.1
	3.2	23.4	43.8	21.6	10.5	11.1
	8.4	26.7	32.1	37.6	24.2	13.4
Silt loam	2.3	5.9	52.1	16.4	5.7	10.7
	6.1	27.1	61.8	30.3	15.9	14.4
	4.5	17.4	56.2	31.2	12.4	18.8
Clay loam	5.1	31.1	37.2	21.0	13.0	8.0
	4.0	36.0	41.3	25.7	13.1	10.6
Silty clay loam	3.2	28.9	53.7	24.4	12.3	12.1

Gravitational Water

The moisture in a soil between saturation (when all voids are filled with water) and field capacity is held by very low tensions, and drains out under natural conditions. Gravitational water is not considered as available water because it does not remain in a soil for any great period of time. This water normally occupies the soil pores that are essential for soil aeration and if the excess water is not removed, plant growth is restricted or delayed.

Hygroscopic Moisture

Moisture in a soil held by forces greater than the permanent wilting value is referred to as hygroscopic. This water occurs primarily as very thin films around soil particles and organic matter. The tension with which this moisture is held is far greater than the extractive power of plants. The hygroscopic moisture content of soils increases with increments of clay and organic matter (Figure 12).

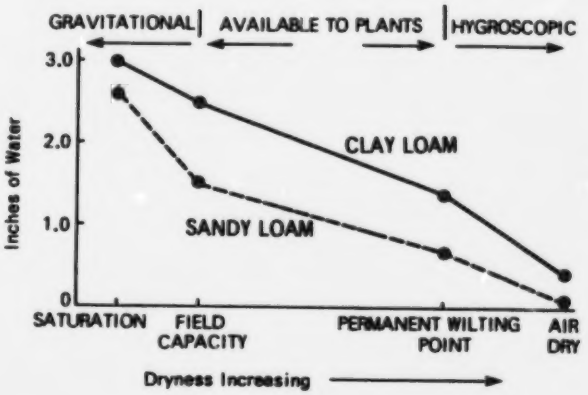

Figure 12. Relationships among the various soil moisture parameters for two soil textures.

Movement of Water in Soils

The movement of water in soils is an example of the flow of a liquid in a porous media. Flow may occur when a soil is saturated or unsaturated. In either case, a driving force is required to initiate and maintain flow. The rate at which water moves through a soil is referred to as the hydraulic conductivity (K) and is expressed as centimetres per second (cm/sec) or inches per hour (in./hr). Other terms to describe water movement include: permeability, permeability coefficient and percolation rate.

Saturated Hydraulic Conductivity (K_{sat})

In a saturated soil, water moves through the soil pores. Normally, the volume of flow is greater in a sandy loam than a clay loam because of the greater volume of large pores in a sandy soil. The K_{sat} value may be obtained experimentally on a natural soil core using an apparatus as illustrated in Figure 13. The quantity of water outflow is actually measured and then used to calculate K_{sat} according to the following equation:

$$K_{sat} = \frac{Q\,L}{t\,A\,P}$$

where K_{sat} = hydraulic conductivity (cm/sec)
Q = volume of liquid outflow (cm^3)
L = length of soil core (cm)
t = time (seconds)
A = cross-sectional area of core (cm^2)
P = pressure head of water (cm)

The K_{sat} value will be expressed as cm per sec per unit cm of pressure, per unit cm of soil thickness and per cm^2 of area (Table 8).

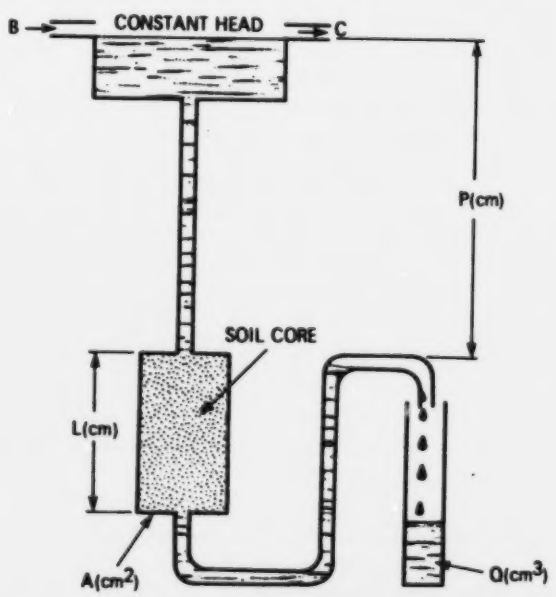

Figure 13. A diagram of the apparatus for the determination of saturated hydraulic conductivity.

The hydraulic conductivity value for soil in a saturated system generally increases with

- an increase in the water stability of the structural units (peds) particularly in fine-textured soils, and
- an increase in the volume of large pores that drain at low tensions.

Conversely, the K_{sat} value normally decreases with

- increasing clay content
- increasing degrees of compaction as measured by bulk density determinations
- decreasing radius of the soil pores

Table 8. Drainage classification and hydraulic conductivity values for soil textural classes

Textural classes	Permeability class	Hydraulic conductivity cm/sec	Hydraulic conductivity in./hr
Gravels, coarse sands	rapid	$>4.4 \times 10^{-3}$	>6.3
Loamy sands and sandy loams	moderately rapid	1.4 to 4.4×10^{-3}	2.0 to 6.3
Fine sandy loams, loams	moderate	0.4 to 1.4×10^{-3}	0.63 to 2.0
Loams, silt loams, clay loams	moderately slow	0.14 to 0.4×10^{-3}	0.2 to 0.63
Clay loams, clays	slow	4 to 14×10^{-5}	0.063 to 0.2
Dense, compacted clays	very slow	$<4 \times 10^{-5}$	<0.063

1.0 in/hr = 0.7×10^{-3} cm/sec

Unsaturated Hydraulic Conductivity (K_{unsat})

A soil is unsaturated when natural drainage stops and the large pores that drain under low tensions are emptied. Water movement approaches zero in a soil at field capacity.

The movement of water in an unsaturated soil occurs by film flow of moisture from one soil particle to another. The driving force causing the moisture flow is due to differing soil moisture tensions within a volume of soil. Water tends to move from areas of low tension to areas of higher tension, that is from moist soil to drier soil. The rate of movement depends on the relative thickness of the water films. As the films decrease in thickness due to an increment in moisture tension, the actual volume of water that moves will decrease because the means of transport (the films) become thinner and lose contact with other films.

Infiltration of Water

When water is added at the surface of a soil, a certain depth of soil, depending on the amount of water added, becomes saturated. If no more water is added, the movement of water continues downward as in unsaturated flow. As the soil moisture content reaches a field capacity value, downward movement ceases.

Infiltration rates are expressed as cm/hr or in./hr and are normally determined in the field if the information is to be used in irrigation or waste water disposal. A technique involves diking an area of land, 2 metres by 2 metres and applying an excess of water. With a measuring stick one can

estimate the rate at which the water is infiltrating. The infiltration rate may also be calculated from rainfall data if the rate of precipitation is known for several minutes. The infiltration rate would be equal to or greater than the known precipitation rate if all the rainfall entered the soil and no runoff occurred. However, runoff and soil erosion occur when the precipitation rate exceeds the infiltration rate for a soil.

Thermal Properties

Thermal properties of soils include temperature, heat capacity and thermal conductivity. These properties vary with the quantity of energy that is received from the sun, the energy that leaves the soil surface, the moisture content, degree of compaction and composition of the soil.

The principal effects of temperature on the soil and plants may be summarized as follows:

- influences biological and chemical reactions in soil
- affects the growth of the higher plants and microorganisms
- determines in part moisture availability
- controls the magnitude of soil heating and cooling

The variations in soil temperature with depth and season of the year or time of day are shown in Figures 14 and 15, for a sod-covered soil at Guelph.

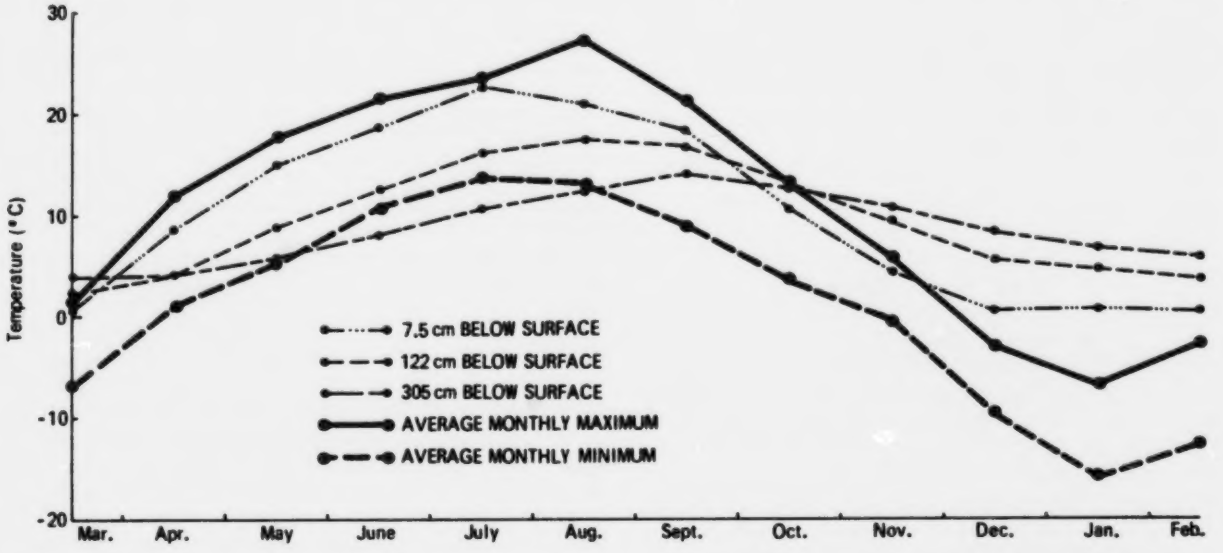

Figure 14. Variations in average monthly temperature for air and three soil depths for the period March, 1969 to February, 1970, at the hydrology station, University of Guelph.

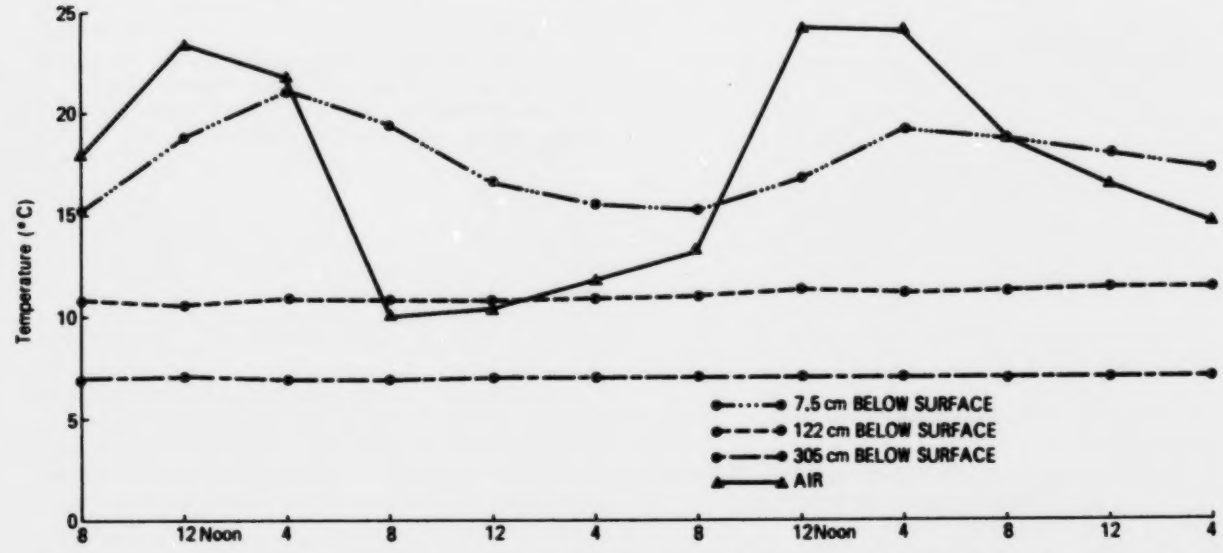

Figure 15. Diurnal temperature variation of air and at three soil depths for the period May 31, 1969 to June 1, 1969, at the hydrology station, University of Guelph.

Heat Transfer in Soils

The solar energy that reaches the surface of a soil may be reradiated back to the atmosphere, used to evaporate water, heat the air above the surface or absorbed. A portion of the absorbed energy causes the soil temperature to rise and induces a downward movement of heat into the soil. The temperature of a soil with depth depends on:

- the thermal conductivity of the soil materials; soil minerals are good conductors while organic matter is relatively poor.
- the moisture content of the soil; the specific heat of water is 1 calorie per gram while that of soil is 0.2 calories per gram[1].

The transfer of heat through soil occurs largely by conduction and primarily through the soil particles; air-filled pores are poor conductors while moisture enhances the transfer of heat. It takes about five times more heat or cold to change a unit weight of water one degree when compared with soil due to the specific heat difference. There is usually a narrow moisture range in a soil when heat transfer reaches a maximum value. Below this moisture value, the air-filled pores restrict heat transfer, while at higher moisture levels more energy is required to heat the water.

Cultivation increases the porosity of a soil and reduces the transfer of heat. Conversely, the compaction of a soil tends to increase heat conduction provided soil moisture is not a significant variable affecting heat transfer. Coarse-textured soils such as a sandy loam warm up in the spring at a faster rate than a fine-textured clay.

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1 *Specific heat of a substance is the quantity of heat (calories) required to raise the temperature of 1.0 g material 1°C.*

CHEMICAL PROPERTIES OF A SOIL

Chemical Composition

The chemistry of a soil is essentially the property of its colloidal content. In soils, all particles < 1 micrometre are said to be colloidal. Because of their tremendous surface area per unit volume, and their peculiar structure, these colloidal-sized particles play a very important role in determining the chemical properties of soils.

The solid phase of soil is a mixture of mineral and organic particles lying in intimate contact so as to provide the skeletal framework for the soil. On the average, 95% of the solid phase is mineral matter, the remainder being organic. The mineral components of soils can be divided into two main groups: first, the original or primary minerals derived from rocks; and second, the secondary minerals formed as alteration or decomposition products of primary minerals. Although about 2000 minerals have been recognized, only a few are of real importance in soils. These include:

feldspars	quartz	limonite
amphiboles	micas	calcite
pyroxenes	clay	dolomite

While many elements have been recognized in the various minerals, eight comprise greater than 98% of the earth's crust. The same elements predominate in our soils but not to the same extent. These elements and their average percentage are shown in Table 9.

Table 9. Eight most abundant elements in the earth's crust and a loam surface soil and their percentage by weight

Element	Earth's Crust	Loam Surface Soil
Oxygen	46.6	45.6
Silicon	27.7	32.1
Aluminum	8.1	5.8
Iron	5.0	2.6
Calcium	3.6	1.0
Sodium	2.8	1.2
Potassium	2.6	1.2
Magnesium	2.1	0.6

With the exception of carbon, hydrogen and oxygen, the soil is the chief source of the nutrients essential for plant growth. Of the 13 essential elements supplied by the soil to the plant only iron, calcium, potassium and magnesium are listed in Table 9. The remaining elements occur in relatively small amounts and are listed in Table 10. The last five occur in such small amounts that they must be considered in terms of parts per million (ppm), which are discussed in more detail in the section entitled Plant Nutrients.

Table 10. Amounts of nine essential elements occurring in a representative loam surface soil

Element	Percentage by Weight	PPM
Nitrogen	0.35	
Manganese	0.25	
Phosphorus	0.11	
Sulfur	0.06	
Zinc		100
Boron		80
Copper		70
Chlorine		70
Molybdenum		2

Mineral Phase

When soils are chemically analyzed only those particles which pass through a 2-millimetre sieve are used. As mentioned in the section on Physical Properties, the mineral portion of this sieved soil can be divided into three fractions; sand, silt and clay. In this arbitrary classification only size is considered. After the organic matter has been removed from the soil, the minerals which make up the sand and silt fractions can be observed under a microscope. The clay fraction cannot be observed under an ordinary microscope because of its size limitation (<0.002 mm) but it has been analyzed by means of more sophisticated techniques (X-ray analysis and electron microscopy).

Sand

- mostly quartz with small amounts of feldspar and mica present
- all grains coated to some extent with iron and aluminum oxide (the rusty, reddish brown color observed is due to the iron)

Silt

- quartz is the dominant mineral
- less feldspar and mica than in the sand fraction
- more iron and aluminum oxides in the form of coatings than in sand fraction. The increase is due to the greater amount of particle surface area on which the coatings may reside

Clay

- finely divided quartz, feldspar, mica, and iron and aluminum oxides – all of these minerals appear in the coarser part of the clay fraction (0.002 mm - 0.001 mm in diameter)
- the finer part of the clay fraction (<0.001 mm) is considered to be of colloidal size and contains mainly layer silicates with smaller amounts of iron and aluminum oxides

The minerals in the sand and silt fractions are made up almost entirely of the elements listed in Table 9. These elements are so arranged that the negative charges possessed by oxygen in the various structures are exactly neutralized by the positive charges of the various other elements present. As a consequence of this electrical neutrality, these minerals do not develop an attraction for other elements and are said to be chemically inert.

Organic Matter

The weathering of minerals is an essential function in the development of soils. A second highly significant and paralleling process is the accumulation of organic matter, the

level of which tends toward an equilibrium in well-developed and well-drained soils. Where the organic matter content approaches an equilibrium level in soils, average annual gains and losses of organic components are about equal. However in poorly drained areas such as bogs, organic matter tends to accumulate.

Soil organic matter includes the remains of plant and animal life in a soil. The main sources of organic matter are the roots, leaves, stems and fruits of plants; the remains of insects, worms, and animals; living and dead microorganisms, and their decomposition products. These sources may be supplemented by farmyard manure, crop residues, and green manure. Chemically, organic matter consists of proteins, carbohydrates, fats, waxes, resins and lignins. The end products of decay tend to accumulate in the soil, usually as a blackish, finely divided colloidal substance, known as humus. This organic material which is always undergoing change is known as the dynamic fraction of the soil (Figure 16).

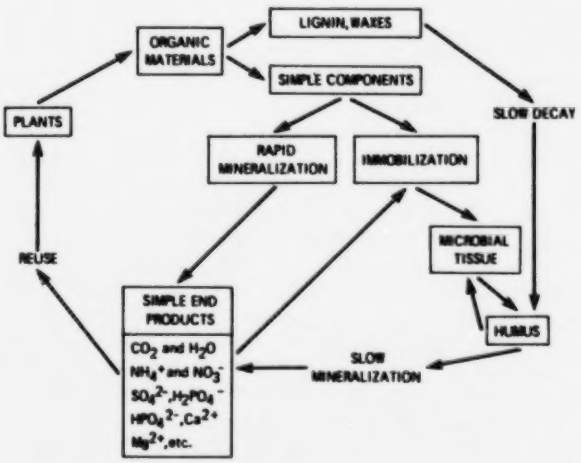

Figure 16. The organic matter cycle in soils.

Since the bulk of the soil organic fraction initially comes from plant residues, it accumulates for the most part within the surface layer, where its presence is evident from the darkening effect it has on soil mineral matter. When organic matter is decomposed to the humus stage, it has certain outstanding properties:

- mostly colloidal in nature
- porous, spongy structure exposes a very large surface area
- takes up large amounts of water and exhibits swelling on wetting, and shrinkage on drying
- peculiar structure allows it to develop a negative charge of varying intensity which in turn is dependent on soil reaction

The level of organic matter in a soil is dependent on two opposing factors: (1) the addition of residues principally from plants, manure and other organic materials and (2) the breakdown of these residues by microbes and other soil organisms. The decay of organic matter in soils is a destructive process – caused principally by microorganisms as they seek nutrients for energy and growth. One of the main reactions in the decay of organic matter is oxidation of carbon compounds by soil organisms to CO_2 and H_2O and is illustrated by the oxidation of a hexose sugar:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 \uparrow + 6H_2O + \text{energy}$$

All plants contribute to the organic matter regime in soils but in varying degrees depending on environmental conditions (Figure 17).

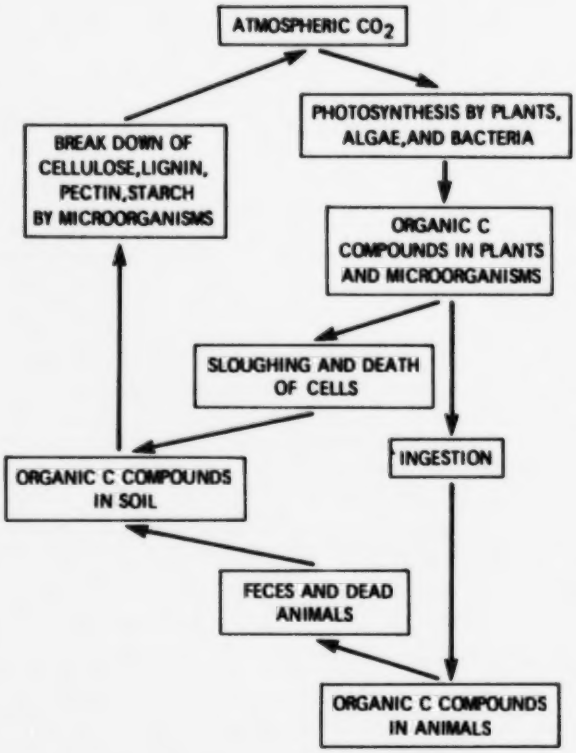
ATMOSPHERIC CO_2
PHOTOSYNTHESIS BY PLANTS, ALGAE, AND BACTERIA
BREAK DOWN OF CELLULOSE, LIGNIN, PECTIN, STARCH BY MICROORGANISMS
ORGANIC C COMPOUNDS IN PLANTS AND MICROORGANISMS
SLOUGHING AND DEATH OF CELLS
INGESTION
ORGANIC C COMPOUNDS IN SOIL
FECES AND DEAD ANIMALS
ORGANIC C COMPOUNDS IN ANIMALS

Figure 17. The carbon cycle.

Organic matter is an important soil constituent because it:

- is a natural source of nitrogen and phosphorus
- acts as a storehouse for essential plant nutrients
- improves the physical conditions of a soil
- reduces erosion losses

Management practices capable of minimizing erosion losses while providing a maximum return of residues are essential for the maintenance of a high level of organic matter in cultivated soils. Optimum crop production through the use of fertilizers, manures or other soil amendments not only provides more cover for erosion control, but also increases production of roots and other unharvested plant parts for addition to the soil organic matter.

Soil Colloids

Clay Colloids

The colloidal layer silicates are referred to as clay minerals. These are secondary minerals that have formed in the soil as a result of the weathering of primary minerals like feldspars and micas. The term "layer silicate" is descriptive of their structure because they exist in soils in layers so thin that they are measured in angstrom units (0.001 mm = 10,000 angstroms). These clay minerals are in the form of very thin plates (<20 angstroms) which are stacked one above the other in a random fashion much like cards in a disarrayed deck. In this way a clay particle is built up, the plates of which are tenaciously held together in some, and only loosely so in others.

However, it is the peculiar structure of these clay minerals that gives this part of the colloidal fraction its dynamic properties. Although the minerals making up the sand and silt fractions are electrically neutral, the clay minerals are not. The crystalline structure of the clay minerals includes oxygen, silicon and aluminum with smaller amounts of magnesium, iron and potassium. During their formation, elements other than those necessary to achieve electrical neutrality became a part of the structure. As a result, all of the layer silicate type clay minerals have an excess of negative charge. The magnitude of this negative charge is not the same for all clay colloids. Those clay minerals which have their plates tightly held together possess a very small negative charge and swell very little if at all in the presence of water. Those minerals which have their plates loosely held together possess a relatively high negative charge and swell considerably when placed in water.

In soils, the extent of swelling and shrinkage depends both on the kind of colloid and the amount of colloid present.

Organic Colloids

Although the structure of the clay colloids is crystalline, that of the organic colloids is amorphous and the elements involved are mainly carbon, hydrogen and oxygen, with smaller amounts of nitrogen, phosphorus and sulfur. Complex chemical groupings are formed, many of which may end with carboxyl (COOH) or hydroxyl (OH) groups. Where these COOH and OH groups are exposed at the surface of the humus colloid, they present possibilities for developing a negative charge because the positively charged hydrogen at the end of these groups tends to dissociate (move away a short distance into the soil solution) when conditions are right. The controlling factor in this dissociation is soil reaction (pH). Under strongly acid conditions (pH<4) dissociation of hydrogen does not occur to any extent. As the soil becomes less acidic (pH>4), dissociation of hydrogen becomes appreciable and continues to at least pH 8.2. Each time a hydrogen ion dissociates, it leaves one negative charge on the humus colloid. By the time most of the exposed COOH and OH groups have lost their hydrogens, the colloid has accumulated a large amount of negative charge which is said to be pH dependent. As a consequence, the higher the pH value, the greater will be the amount of negative charge possessed by the colloid.

Soil Cations and Anions

Collectively, the available forms of elements in the soil are referred to as ions. Those ions carrying a positive charge are called "cations", and include calcium, potassium and magnesium. Those ions carrying a negative charge (generally combined with oxygen) are called "anions". These include nitrate, phosphate, sulfate, bicarbonate, molybdate, and borate. Although not taken up by plants, hydrogen also is an important cation. Its role in soil reaction will be discussed in a later section.

Cation Exchange

The section on soil colloids has emphasized the fact that both the clay and humus colloids are negatively charged. This is not intended to imply that the colloids do not achieve electrical neutrality. They do. The positively charged cations set free in the soil solution during weathering of the soil minerals are attracted to the negatively charged colloids and tend to be adsorbed on their surface. (Adsorption refers to the adhesion of substances to the surfaces of solids. In soils it refers to the attraction of substances for colloidal surfaces.) Sufficient cations are adsorbed to completely neutralize all of the excess negative charge possessed by the colloids. The cations which are usually adsorbed are calcium, magnesium, hydrogen, aluminum, potassium and small amounts of sodium and ammonium. (At pH 6 or higher, aluminum forms insoluble compounds and will no longer be adsorbed.)

The cations adsorbed on the colloidal surfaces are not held very tightly. They resist removal by water draining through the soil but can be removed by plant roots. More important still, they may be replaced or exchanged by other cations in the soil solution. When a cation held on a soil colloid is replaced by a cation in the soil solution, cation exchange is said to have taken place. The cations held on the colloidal surfaces are said to be exchangeable and their numbers usually far exceed the same kinds of cations present in the soil solution. In this respect, the cations held on the colloids act as a reserve which continually resupplies the soil solution, through the medium of cation exchange, with nutrients required by the plants. However, the reserve eventually becomes exhausted. When soils become acidic, it is because the reserves of calcium and magnesium have been used up in exchange for hydrogen and aluminum, and they can only be restored by the addition of ground limestone. It is this process of cation exchange which permits the calcium and magnesium reserves to be restored. When soils are near neutral or alkaline in reaction, calcium is the dominant exchangeable cation present. Acid soils result when hydrogen and/or aluminum are the predominant cations.

The cation exchange capacity of a soil is a measure of the concentration of cations required to neutralize all of the negative charges (exchange sites) possessed by a unit weight of soil. The magnitude of the cation exchange capacity depends upon the kind and amount of colloidal content. Organic colloids have a much greater cation exchange capacity than clay colloids. A high cation exchange capacity is desirable providing the soil is well drained and the clay content not so high as to impede tillage operations. The exchange capacities for five soils are given in Table 11.

Table 11. The cation exchange capacity (CEC) and colloid contents of five soils of different textures

Soil Texture	Organic Matter %	Clay %	CEC* me/100 g
Sand	1.7	7	6.3
Sandy loam	3.2	13.2	13.7
Loam	4.9	16.8	20.2
Silt loam	5.4	18.4	24.0
Clay loam	5.5	31.2	27.2

**The cation exchange capacity of a soil is expressed in terms of milliequivalents per 100 grams of soil (meq/100 g). A milliequivalent is defined as 1.0 milligram of hydrogen or the amount of any other element that will combine with or displace it. The milliequivalent weight of any element may be found as follows:*

$$\frac{\text{atomic weight of element}}{\text{valence of element} \times 1000} = \text{milliequivalent weight}$$

Anion Retention

The colloids of Ontario soils exhibit very little, if any, anion exchange. The retention of anions in the soil for plant use therefore depends on other mechanisms. Their maintenance in an available form is usually more of a problem than is the case with cations. All nitrates are water soluble and hence easily carried away by rainwater. Fortunately, most of the nitrogen in the soil is present as part of the organic matter. While not available to plants in this form, it is slowly mineralized (see section on Plant Nutrients) to an available state. Sulfur in the form of sulfate is also readily leached from the soil. Again, most of it is preserved against loss as part of the organic fraction and like nitrogen is slowly released in a form that the plant can use. The phosphate anion presents a different problem in that it is difficult to keep it in the soil in a form which the plant can use. It is present in both organic and inorganic combinations. Organic phosphorus does not become available as easily or as quickly as do nitrogen and sulfur. The various native inorganic phosphates are present in very small quantities which are usually insoluble in water. When phosphorus fertilizers are added to the soil, they are changed to relatively insoluble calcium phosphates, if the reaction is neutral or alkaline, or, to more insoluble iron and aluminum phosphates if the reaction is acidic. Molybdenum and boron are two elements required by plants in very small amounts. As indicated by Table 10, they are present in soils in small amounts. Like phosphorus, their main problem is availability. Both exist primarily as inorganic compounds and their availability is determined to a considerable extent by pH. Boron (as borate) is most soluble under acidic conditions while molybdenum (as molybdate) is most soluble under neutral to alkaline conditions. Chlorine in the form of chloride is almost as soluble as nitrate. The addition of chlorine in rainwater and as a component of fertilizers provides the necessary requirements for plant use.

Soil Reaction and the pH Scale

Perhaps the most important chemical characteristic of a soil is its reaction, that is, its degree of acidity or alkalinity. Whether a soil is acidic, neutral, or alkaline profoundly affects the nature of its chemical and physical properties, and hence, suitability as a medium for the growth of various species of plants.

The reaction of every mixture of soil and water is determined by its content of hydrogen (H^+) and hydroxyl (OH^-) ions. Water is a source of both of these ions.

1. water molecules – HOH – which are neutral
2. hydrogen ions – H^+ – which are acidic
3. hydroxyl ions – OH^- – which are alkaline or basic

In pure water very few H^+ and OH^- ions are present, in fact only one molecule in every 554 million dissociates into H^+ and OH^- ions. However, when salts or gases are dissolved in the water (as is always the case in soils) then many more H^+ or OH^- ions are produced depending on whether the substance dissolved is an acid or base former. When a soil is acidic in reaction, it is because the concentration of hydrogen ions (H^+) exceeds that of hydroxyl ions (OH^-) in the soil water. When the concentration of both ions is equal, the reaction is neutral.

The pH scale has been devised for conveniently expressing the very small concentration of H^+ ions found in many biological systems including soils. The pH scale[1] goes from 0 to 14 with pH 7 being neutral. Any value below 7 indicates acidity and any value above 7 indicates basic or alkaline conditions.

The major effects of soil pH are biological. The actual concentrations of H^+ and OH^- ion are not very important except under the most extreme circumstances. As will be shown in later sections, it is the associated conditions of a certain pH value that are most important.

Reaction of Ontario Soils

The tendency for all soils in the humid temperate region is to become acidic. In Ontario, which is a part of this region, the reaction of most soils varies between pH 6.0 and 7.5. Three factors are mainly responsible for this:

- large amounts of basic elements like calcium and magnesium are present in the soil (the residue of weathered limestone parent materials)
- short period of exposure time to weathering
- limited amount of leaching takes place (removal of basic elements in solution by rainfall moving through the soil)

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[1] *It is important to remember that the pH scale is logarithmic in nature as pH is defined by:*

$$pH = \log \frac{1}{[H^+]}$$

where $[H^+]$ equals moles of H^+ per litre. The pH of pure water is calculated as follows:

$$pH = \log \frac{1}{0.0000001} = \log 1 \times 10^7 = 7$$

When the H^+ concentration is 0.00001 moles per litre then

$$pH = \log \frac{1}{0.00001} = \log 1 \times 10^5 = 5$$

Similarly when the H^+ concentration is 0.0001 moles per litre, the pH is 4. As a consequence of its logarithmic nature it can be seen that at pH 6, the H^+ concentration (acidity) is 10 times greater, and at pH 5 it is 100 times greater than at pH 7.

Some Ontario soils have not weathered sufficiently to remove all of the original limestone (calcium carbonate) and may have pH values as high as 8.3. Other soils have pH values below 5.0 and are considered to be strongly acidic.

Soil acidity is caused by one or more of the following conditions:

- a natural condition where soils have formed from acidic parent materials low in bases
- the decomposition of organic residues as a result of biological activity producing both organic and inorganic acids which are sources of hydrogen ions
- the application of nitrogen fertilizers especially those containing ammonium which undergo nitrification. (See section on Biological Properties of a Soil.) This results in the formation of nitric acid which increases soil acidity.
- the loss of bases by crop removal or by leaching. Crops remove basic ions like calcium, magnesium and potassium from the soil. These are at least partially replaced by hydrogen. Calcium and magnesium are always removed to some extent when rainfall leaches through the soil.

It should be mentioned that the aluminum ion, while not acidic itself, is an acid former. This occurs because soluble aluminum combines with the hydroxyl ions (OH^-) of water to form various compounds. In doing so it leaves the dissociated acidic hydrogen ion (H^+) to increase the acidity of the soil solution, which explains how most of the acidity develops below a pH of 6.

Soil acidity can be corrected (neutralized) by the additions of ground limestone (calcium carbonate) or dolostone (calcium-magnesium carbonate). The practical significance and methods of controlling soil reaction are discussed in the section, Soil Management.

BIOLOGICAL PROPERTIES OF A SOIL

The biological population of a soil is an intimate part of the organic fraction. Only a small part (perhaps in the range of 0.1 to 2%) of the organic material in soil is actual living tissue, but a large part of the colloidal fraction of humus consists of the remains of biological cells. The characteristics of organic residues from plant and animal sources and the availability of plant nutrients from such materials are the direct result of the biological activity in the soil.

The biological population can be considered to consist of a microflora, which includes bacteria, actinomycetes, fungi and algae; and an animal population which comprises protozoa, nematodes, segmented worms and arthropods.

Microorganisms

Bacteria

The bacteria are the most numerous of the microorganisms in the soil. Estimates range from 10 to 100 million in one gram of soil, but may vary widely in any soil depending on the availability of energy supplies. Many types of bacteria exist in soil. For simplification it is convenient to divide bacteria into several groups based on their metabolic needs. On the basis of their energy source, bacteria can be termed heterotrophic or autotrophic.

Heterotrophic bacteria account for most of the bacteria found in soil. The heterotrophic organisms require organic compounds for their energy and carbon needs. Virtually every organic compound that is produced in the soil or is added to the soil in any way is subject to decomposition by some heterotrophic organism.

Autotrophic bacteria obtain their energy from the transformations of inorganic compounds and their carbon from CO_2. Only a few bacterial species are autotrophs but because of the reactions they are involved in, they have a great importance from the agronomic and environmental standpoint.

Another way of describing bacteria on the basis of their metabolic requirements is from the standpoint of their oxygen requirements.

Aerobic organisms require free atmospheric oxygen (O_2). Most of the heterotrophic and essentially all of the autotrophic organisms are aerobic organisms. A few may be able to remain active where oxygen is lacking but for most, free O_2 is essential. Decomposition of organic material by aerobic organisms is more complete, terminating with end products such as carbon dioxide (CO_2), water (H_2O), ammonia (NH_3) and nitrate (NO_3).

Anaerobic organisms do not require free oxygen for their metabolism. Organic material is not broken down completely in the absence of oxygen. The end products tend to be incompletely oxidized organic compounds. A characteristic of an anaerobic decomposition is the foul odor associated with putrefaction of protein material.

Actinomycetes

The actinomycetes are numerous and widespread in soil, second in number to the bacteria. They are aerobic, heterotrophic organisms and thus are involved in the decomposition of organic residues in soil. Soils that are acidic will restrict the growth of actinomycetes, with very few growing below pH 5. Actinomycetes can grow abundantly on residues with moisture contents lower than can be tolerated by either bacteria or fungi. Under ideal moisture conditions actinomycetes appear to be unable to compete with the fungi or bacteria.

Some species of actinomycetes produce antibiotics. The most commonly used antibiotics obtained from actinomycetes are streptomycin, terramycin, aureomycin and others.

Fungi

The fungi are not as numerous as bacteria or actinomycetes. However, because their cell size is so much larger, the biomass of the fungi is probably greater than for either the bacteria or actinomycetes, and consequently the fungi are of considerable importance in soil processes. All fungi are heterotrophic and almost all are aerobic organisms. Thus the fungi are found primarily in the aerated surface layers rich in organic matter. Fungi grow best near neutrality but are much more tolerant of acidic conditions than bacteria or actinomycetes. In acid soils therefore, the fungi have little competition and are the major group of microorganisms present.

Algae

Algae are mostly chlorophyll-bearing organisms and to survive they must live at or very near the soil surface. Their activity appears to be related to the decomposition of organic matter and the release of plant nutrients. Algae are often associated with poorly drained soils.

Animal Population

Animal population in a soil includes protozoa (one-cell organisms), nematodes (microscopic worms), segmented worms (earthworms) and arthropods (large and small insects). Generally, these animals are found in greatest numbers in or near the surface soil. Many of them depend on nonliving organic matter as a source of food (protozoa); others infest roots causing plant injury (nematodes). The earthworms pass large amounts of soil and organic matter through their bodies thus assisting in the breakdown of soil materials and the release of plant nutrients. The insects are active in soil burrowing, organic matter decomposition and in providing food for other organisms.

Biological Reactions in Soils

Organic Matter Decomposition in Soil

Most biological reactions involve transformations in and the decomposition of soil organic materials. The decomposition of organic matter is the end result of the activity of

heterotrophic organisms in the soil. Some organisms can utilize a wide variety of compounds, while others are very specific in their metabolic needs. The initial rate may be very slow because of the low numbers of the particular organism, unfavorable growth conditions or the time required to develop appropriate enzyme systems. It is important to note that in a natural soil, decomposition can be considered a team effort among many different organisms, one acting upon the partly decomposed products of the preceding ones.

The rate of organic matter decomposition and the type of products formed will vary, depending on the conditions that prevail in the soil environment which may disturb or control the equilibrium of microbial species, suppressing one type of organism in favor of another.

Several factors influence the decomposition process. These are:

pH – generally values around neutrality favor decomposition by bacteria, particularly if adequate available nitrogen is present. At neutrality (pH 7.0) bacteria grow more rapidly than fungi and thus tend to dominate the population. At acidic (low) pH, bacteria are generally more inhibited and fungi which are more tolerant become the dominant species. The dominance by bacteria or fungi tends to alter the decomposition process slightly as bacteria convert more of the residue to inorganic materials such as CO_2, NH_3, and H_2O, while fungi tend to incorporate more of the carbon into tissue. Eventually the fungal hyphae die and are decomposed, and thus the end result may not be greatly different.

Aeration – With limited oxygen, the aerobic, heterotropic organisms are inhibited in their decomposition of organic materials and the anaerobic organisms become active. Generally, under anaerobic conditions, decomposition is slower and the products are modified. Instead of CO_2, NH_3, H_2O etc as the final products, anaerobic decomposition yields organic acids, some CO_2, hydrogen, methane, hydrogen sulfide and resistant organic compounds that anaerobic organisms cannot utilize. An important result of anaerobic decomposition is that the products frequently have an objectionable odor. Anaerobic conditions are not desirable in soils, and conditions leading to anaerobic decomposition processes should be avoided.

Temperature – Within the range of microbial growth, decomposition is faster at the higher temperatures, although the common soil organisms generally grow in the range of 0 to 45°C. As temperatures approach zero, decomposition slows considerably. Thus in the winter months, there is little decomposition.

Moisture – A minimal amount of available water in a soil is required for the growth of microorganisms. Beyond the required minimum, the relationship between the amount of water and aeration of the soil is quite important. If excess water is present, anaerobic conditions will develop, resulting in a completely different decomposition process.

Composition and state of the organic residue – The nature of organic materials that find their way into soils can have a significant influence on the decomposition processes. Fresh succulent material will decompose much more readily than older more mature tissues. Mature plants contain more hemicellulose, cellulose and lignin which are more stable, and are attacked by a much smaller range of organisms. Thus the rate of decomposition of such material tends to be slower.

The chemical composition, in particular the carbon to nitrogen ratio, also influences the rate of decomposition. If the C/N (carbon to nitrogen) ratio is generally less than 25 and if the material is not too mature or fibrous, then decomposition will proceed rapidly. However, if the ratio is greater than 25, the initial decomposition will be slower due to a deficiency of nitrogen to accommodate the rapid increase in microbial population that usually accompanies an organic residue addition. If rapid decomposition of material with a wide C/N ratio is necessary, then the addition of nitrogen fertilizer will provide the needed nitrogen.

The physical state, or particle size, will also affect decomposition. Smaller particles provide more surface area for attack by organisms. Slower decomposition can thus be anticipated if very coarse material is added to soil.

The Nitrogen Cycle

The transformations of nitrogen (N) in soil can be most easily illustrated by the nitrogen cycle (Figure 18).

The main steps in the N cycle can be described as:

Mineralization – the decomposition by a wide range of aerobic heterotrophic organisms to release organic nitrogen. Nitrogen in excess of the organism's requirements is released as NH_4^+.

Nitrification – two specific groups of aerobic autotrophic organisms utilize the NH_4^+ as follows:

Nitrosomonas: $2\,NH_4^+ + 3\,O_2 \rightarrow 2\,NO_2^- + 4\,H^+ + 2\,H_2O$ + energy

Nitrobacter: $2\,NO_2^- + O_2 \rightarrow 2\,NO_3^-$ + energy

In this way these autotrophic organisms have obtained energy from the oxidation of nitrogen. The result is the transformation of NH_4^+ to NO_3^-. There is generally very little accumulation of NO_2^- in soils.

Utilization and immobilization – nitrogen in the form of NH_4^+ or NO_3^- can be utilized by plants or immobilized by microorganisms if they have a need for nitrogen. Immobilization occurs if residue with a wide C/N ratio is being decomposed. Immobilized nitrogen may be released when the organisms die.

Denitrification – occurs in soils under anaerobic conditions. The oxygen in the nitrate is utilized by certain groups of organisms and the nitrogen is released as gaseous N_2. This results in a loss of nitrogen from the soil system.

$$4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O$$

Nitrogen fixation – a natural biological process that results in the change of atmospheric N_2 to other nitrogen compounds in the soil as a result of the activity of specific microorganisms.

- Symbiotic nitrogen fixation. Organisms of the genus Rhizobium can infect the roots of legume plants (e.g. alfalfa, clover, beans, peas) and cause the formation of characteristic nodules. Rhizobia living in the nodules obtain energy material from the plant roots but they are capable of obtaining their nitrogen from atmospheric N_2. Some of the nitrogen that is fixed from the air is available to the infected plant. Thus a mutually beneficial or symbiotic relationship exists.

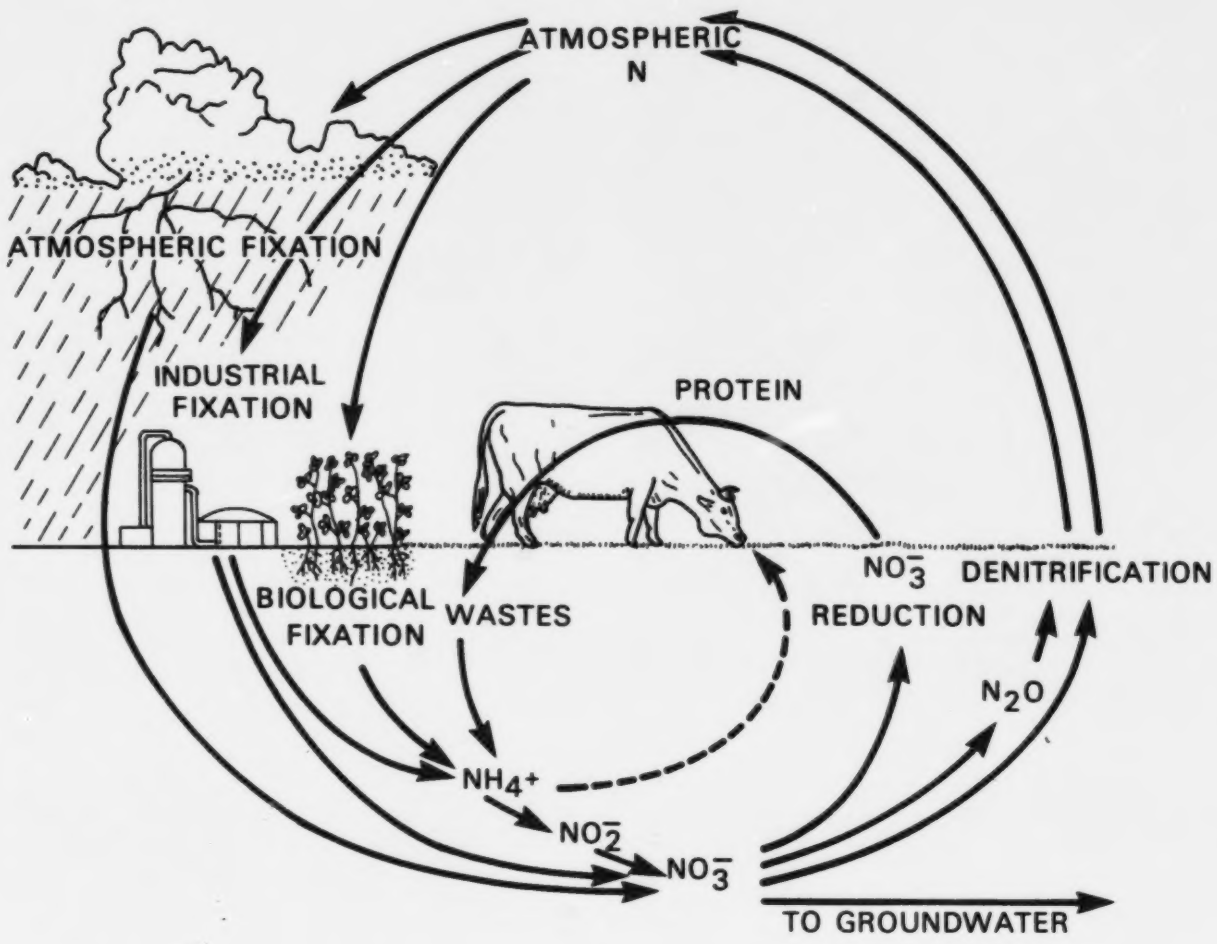

Figure 18. The nitrogen cycle.

The plant obtains nitrogen from Rhizobia while the Rhizobia obtain nutrients from the plant. This is an important economic relationship since legume plants can be grown on soils low in available nitrogen without the requirement of nitrogen fertilizers.

– Nonsymbiotic nitrogen fixation. It is carried out by two groups of organisms, Azotobacter and Clostridium. In this case these organisms fix atmospheric nitrogen for their own use. However, nitrogen that is fixed can become available in the soil as the microorganisms die.

Leaching – refers to water moving through the soil. Nitrate form of nitrogen is very soluble in water. As water moves through a soil, any nitrogen in this form will be transported by the water. Therefore in a soil where a net movement of water exists there will be a loss of nitrogen by the leaching process.

Importance of Microorganisms in Soil

From the standpoint of crop production, the greatest effect by any microorganism is on the nitrogen availability in soils. About 95% of the nitrogen in surface soil occurs in organic compounds. The nitrogen is released according to the reactions described in the nitrogen cycle. If nitrogen is to be available from added residues, then the carbon to nitrogen (C/N) ratio is important. With residues of high C/N ratio, nitrogen is immobilized by the microorganisms and a crop could become nitrogen deficient. If nitrogen is released by microbial action, the other reactions will also occur depending on the prevailing conditions. That is, nitrification will proceed under aerobic conditions. The NO_3^- produced is subject to loss through leaching if a crop does not absorb it.

PLANT NUTRIENTS

Soil is the chief source of elements essential for plant growth other than carbon, hydrogen and oxygen. Each nutrient occurs in one or more chemical forms in a soil, each form differing in its availability to a plant. Since plants absorb nutrients largely from the soil solution, availability is controlled by the amount of the nutrient in soil solution, and the ease and rate with which a nutrient goes into the soil solution. As the soil water or soil solution moves to the root to supply the plant with water, ions are carried along with it to the root surface where they may be absorbed into the root (Figure 19). It is also possible that nutrient ions move to the root surface by diffusion, that is, as ions are absorbed, the ion concentration at the root surface decreases causing more ions in the soil solution to move into the zone of low concentration. In any case, a prerequisite for ion absorption is the proliferation of roots and root hairs into the soil mass.

The forms of nutrients in the soil may be classified as follows:

- difficulty available – nutrients in rocks and minerals that are slowly released by the weathering of the rocks and minerals – slow decomposition of stable forms of organic matter
- moderately available – nutrients in easily decomposible organic matter and fixed in mineral particles that are released at a moderate rate into the soil solution
- readily available – nutrients in the soil solution or absorbed onto clay or organic particles such as exchangeable cations

Clay and organic particles are the storage reservoir of the soil because they hold nutrient cations such as calcium, magnesium, and potassium on their surfaces and by an exchange process readily release these ions into the soil solution for absorption by plants. Other nutrients such as nitrogen, sulfur and phosphorus which exist in the organic form are released during microbial decomposition of organic matter.

A soil with a large storage reservoir is not necessarily a fertile soil. Continued cropping may deplete one or more of the available nutrients more rapidly than they are replenished. Ideally, each plant nutrient should be present in a soil in varying degrees of availability so that both the immediate and long-term needs of the crop will be satisfied. Replenishment of nutrients in the storage reservoir comes from weathering of soil particles and from the application of fertilizers and animal manures.

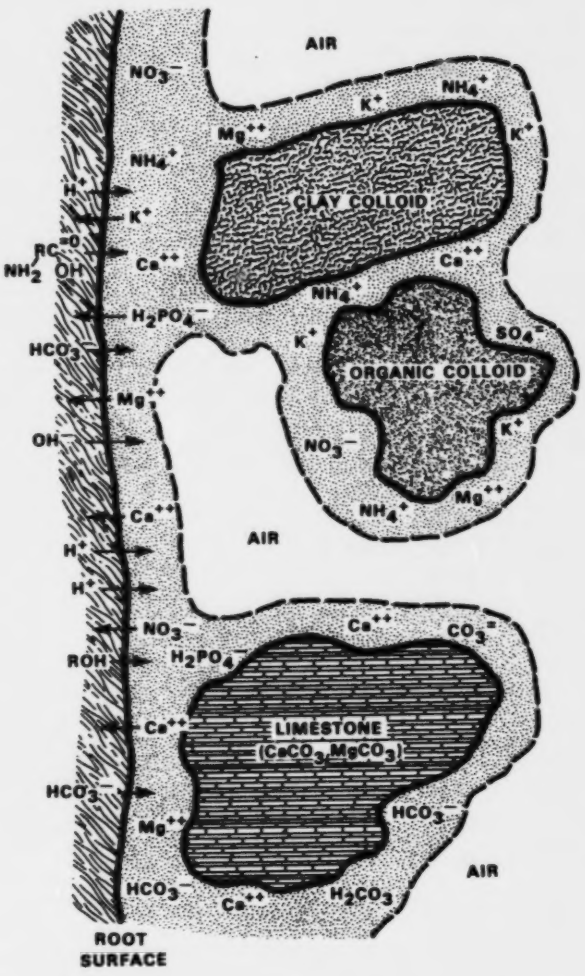

Figure 19. A diagrammatic representation of the root-soil interface. Ions which result from organic matter decomposition, or are released from the mineral soil particles, move with or through the soil solution to the root surface where they are absorbed into the root. Although soil particles may occur in close proximity to the root surface, ions still move over very short distances to the sites of absorption at the root surface. During the absorption process, hydrogen (H^+) ions are exchanged for nutrient cations while hydroxide (OH^-) and bicarbonate (HCO_3^-) ions are exchanged for nutrient anions. Also, organic molecules such as organic and amino acids are released from plant roots. These exudated substances help to sustain microorganisms which occur adjacent to root surfaces. Some H^+ and OH^- ions combine to form water while HCO_3^- ions may combine with H^+ to form carbonic acid (H_2CO_3) which in turn degrades to CO_2 and H_2O.

Macro- and Micronutrients

Many elements are contained in a plant but at least sixteen are known to be essential for plant growth. An element is said to be essential if the plant cannot complete its life cycle without it. Elements are classified as macronutrients or micronutrients depending on the relative amounts

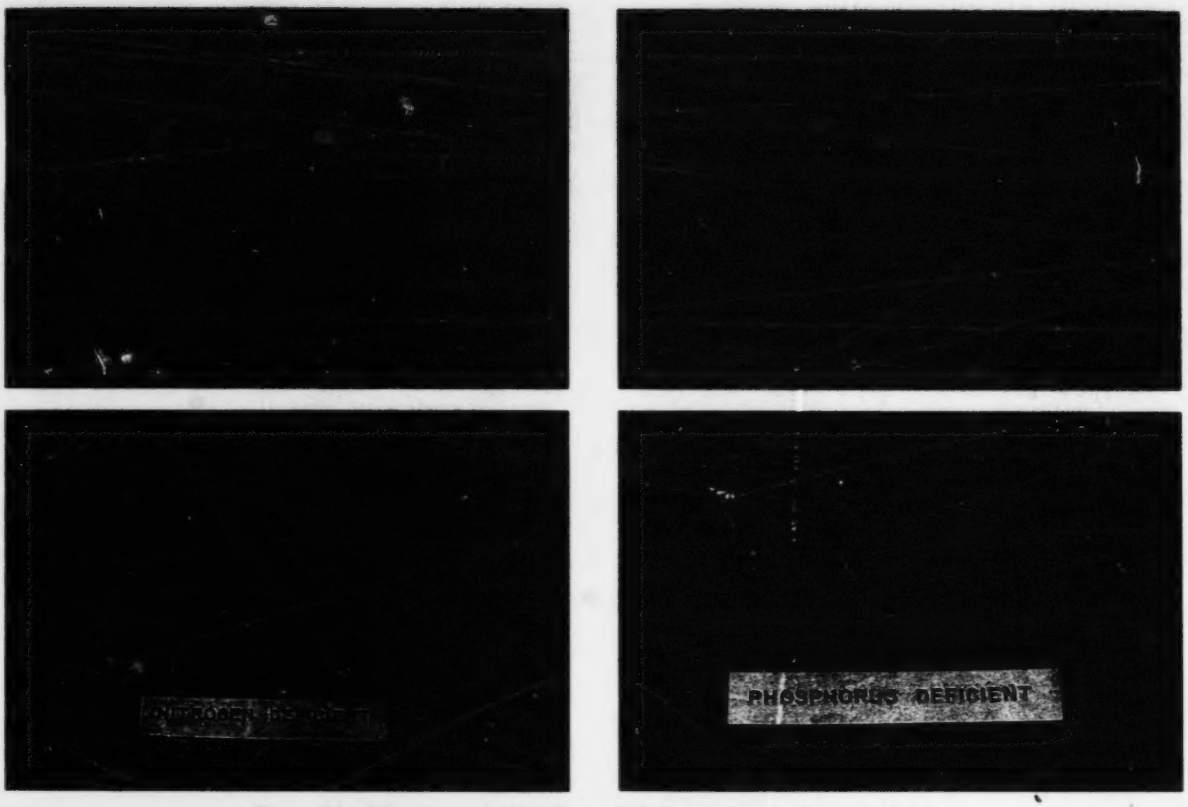

Figure 20. Nitrogen and phosphorus deficiencies in corn leaves and ears.

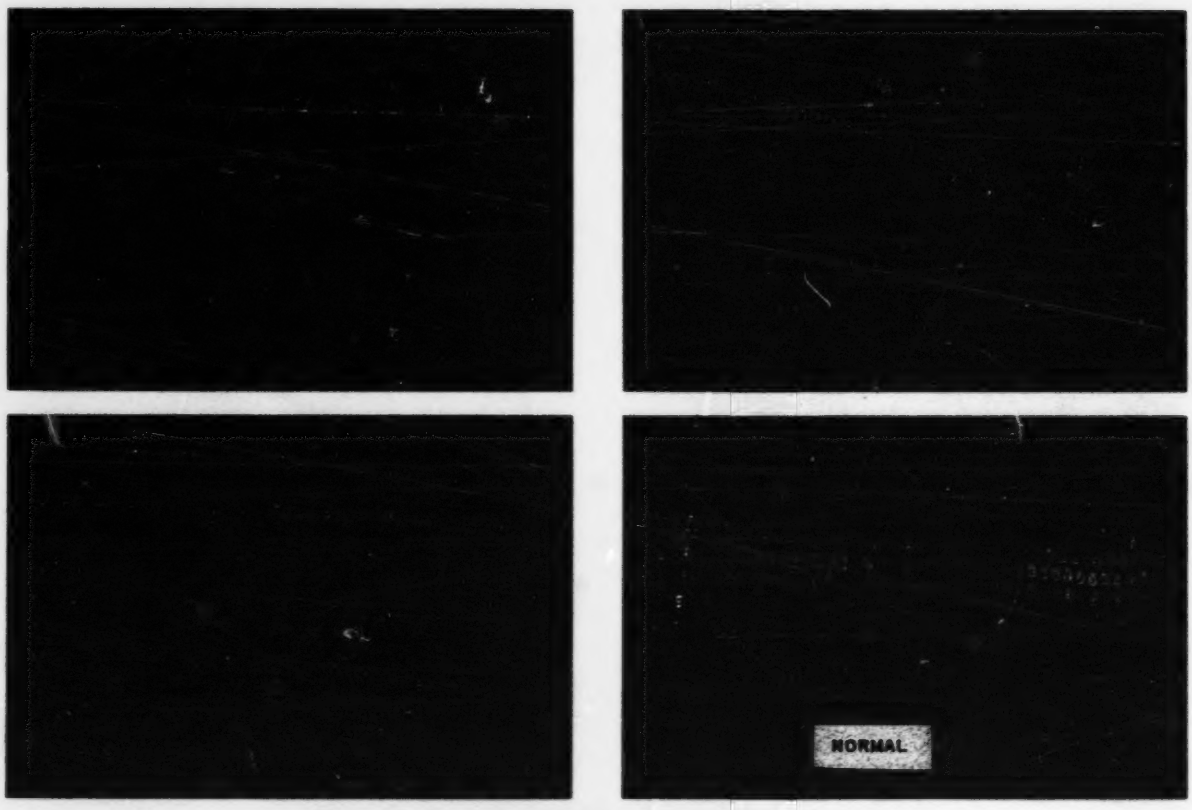

Figure 21. Potassium deficient and normal corn leaf and ear.

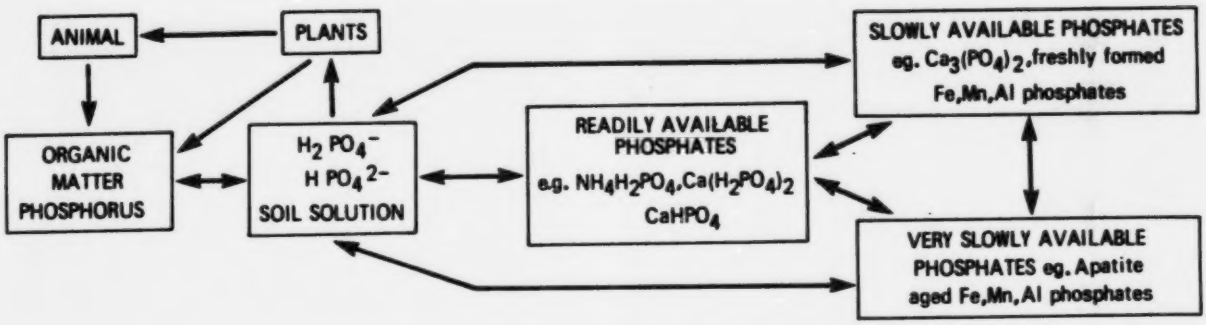

Figure 22. A simplified version of the phosphorus cycle in the soil-plant-animal system.

(not relative importance) in plants. The essential elements are listed below.

Macronutrients	Micronutrients
nitrogen (N)	boron (B)
phosphorus (P)	copper (Cu)
potassium (K)	iron (Fe)
calcium (CA)	manganese (Mn)
magnesium (Mg)	molybdenum (Mo)
sulfur (S)	zinc (Zn)
	chlorine (Cl)

Carbon, hydrogen, and oxygen are the main building elements of plant tissues comprising over 90% of the plant weight. Plant tissues are composed of approximately 45% carbon, 43% oxygen and 6% hydrogen. Plants obtain the hydrogen from water, oxygen from the atmosphere and carbon from carbon dioxide in the atmosphere.

The concentration of the remaining nutrients depends on several factors including species, genotype, plant part (leaf or stem), age, nutrient supply in soil, soil temperature and moisture. An example of ranges of nutrient concentrations (oven-dry weight basis) which may normally be found in corn plants is shown in Table 12.

The macronutrient concentrations are normally much higher than the micronutrient concentration (1% = 10,000 ppm), which may mean that plants require much smaller quantities of micronutrients than macronutrients.

Plant growth will be inhibited if the supply of nutrients in the soil is deficient or excessive.

Figure 23. Magnesium deficiency in corn. Note the yellow interveinal striping running the full leaf length.

Table 12. Nutrient concentrations in corn plants

Nutrient	Concentration (% by weight)		
	Young Plants 3-4 leaf stage	Ear Leaf Silking Stage	Grain at Maturity
Nitrogen (N)	3.5-5.0	2.7-3.5	1.0-2.5
Phosphorus (P)	.4-.8	.2-.4	.2-.6
Potassium (K)	3.5-5.0	1.7-2.5	.2-.4
Calcium (Ca)	.9-1.6	.4-1.0	.01-.02
Magnesium (Mg)	.3-.8	.2-.4	.09-.2
Sulfur (S)	.2-.3	.1-.3	-
		(ppm)	
Boron (B)	7-25	4-15	-
Copper (Cu)	7-20	3-15	1-5
Iron (Fe)	50-300	50-200	30-50
Manganese (Mn)	50-160	20-250	5-15

Plants may also contain other elements whose concentrations in plants is normally low. If the supply of some of these elements in the soil becomes too great, plant growth may be adversely affected or the usefulness of the plants for food or feedstuff may be restricted.

Nitrogen, phosphorus, and potassium are required in relatively large quantities by plants and comprise the bulk of the nutrients bought as commercial fertilizers.

Macronutrients

Nitrogen – A deficiency of available nitrogen in the soil probably limits plant growth more often than any other nutrient (Figure 20). Although 80% of the atmosphere is N_2 gas, it is not directly utilized by plants. Nitrogen also occurs in several forms in the soil but most of these are complex organic forms. Nitrogen is a major component of protein in plants and is therefore important for crop quality. It is also required by soil microorganisms for organic matter decomposition.

The primary source of soil nitrogen is gaseous N_2 in the atmosphere. However, in order to be used by plants it must be transformed to another form which usually involves combination of nitrogen with hydrogen or oxygen. This combination may be brought about in any one of the following ways.

(1) Discharges of lightning result in the combination of nitrogen with oxygen. The nitrate ion formed is then transported into the soil by rain. The amount of nitrogen added to the soil by this means is small and varies from 2 to 10 pounds per acre per year.

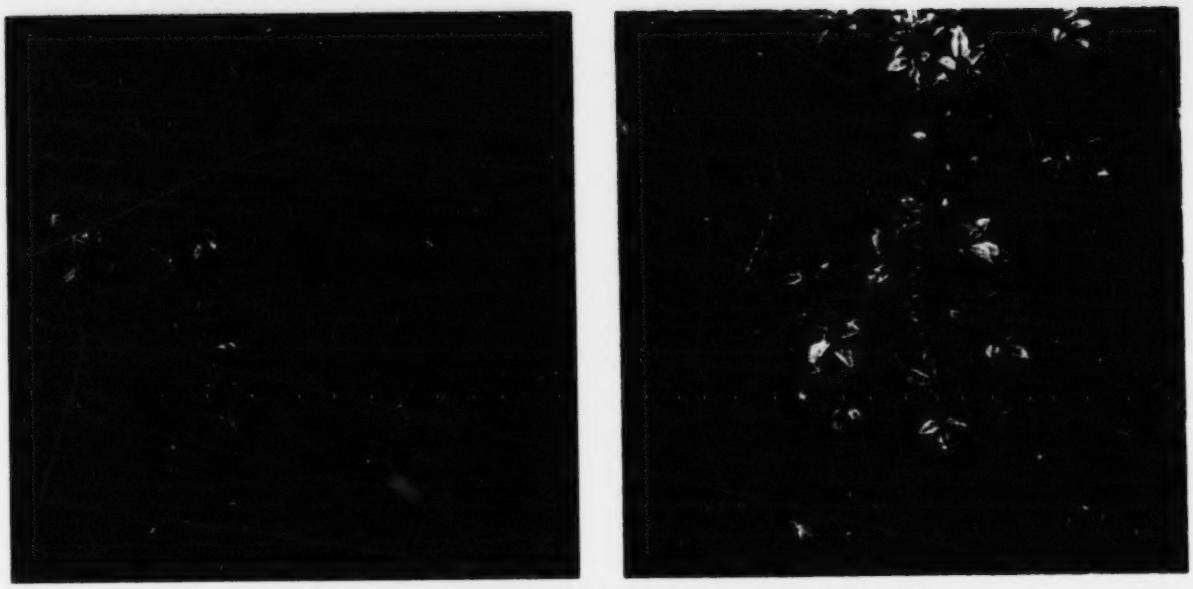

Figure 24. Boron deficiency in alfalfa. Note the stunting and color change.

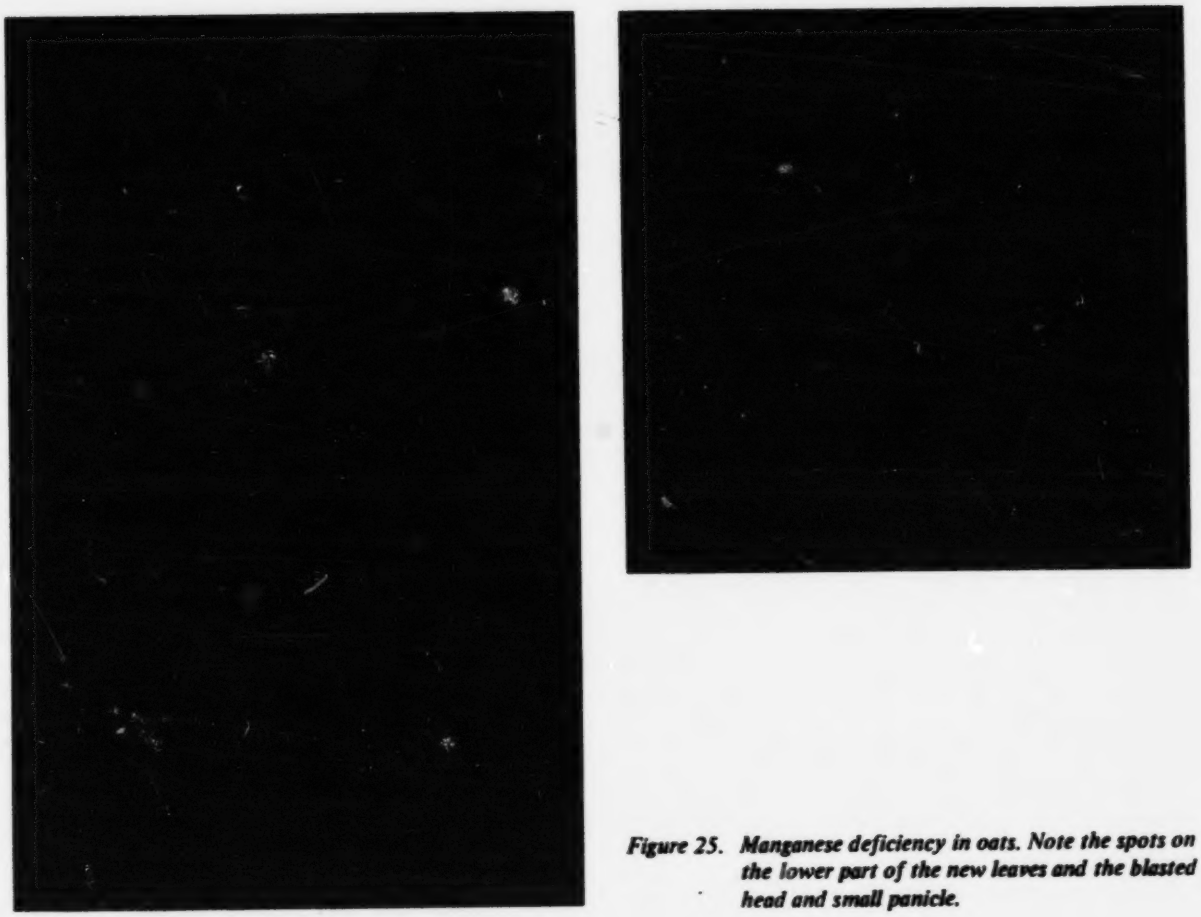

Figure 25. Manganese deficiency in oats. Note the spots on the lower part of the new leaves and the blasted head and small panicle.

(2) Industrial processes combine gaseous nitrogen with hydrogen to form ammonia (NH_3). This is the main commercial source of nitrogen for fertilizer use. It should be noted that these processes require large energy inputs; approximately 38,000 cubic feet of natural gas is required to produce one ton of ammonia.

(3) Nonsymbiotic microorganisms that occur in the soil and symbiotic microorganisms (Rhizobia *spp*) which live in nodules on roots of leguminous plants, such as alfalfa and soybeans, retain nitrogen in the soil by a process called fixation. Symbiotic microorganisms in association with alfalfa may fix between 50 and 530 pounds nitrogen per acre per year.

The complex nature of nitrogen in the soil-plant-animal system has been described previously in the section Biological Properties of a Soil.

The slow release of ammonium and nitrate nitrogen from organic forms during the growing season is the natural way of supplying plants with most of their nitrogen requirement. However if the rate of release is not adequate, nitrogen fertilizer should ideally be applied as close as possible to the time when the plants need it most. This will be explained in the section Soil Management.

Phosphorus – The use of phosphorus-containing materials for improving soil productivity is an old practice. Animal bones were applied to soil as a source of phosphorus in England in the early 17th century. Phosphorus in soils and plants usually occurs in combination with other elements including oxygen, in which case it is referred to as phosphate.

Phosphorus promotes rapid and vigorous growth and seed development. As a component of some organic molecules in plants, its primary role is the transfer and storage of energy for biochemical reactions. It also has a structural role in a number of compounds.

Phosphorus occurs in two forms; inorganic or mineral such as apatite (a calcium-phosphate- fluoride compound), iron and aluminum phosphates; and organic as complex compounds in the soil organic matter. About one-half of the phosphorus in many Ontario soils occurs in the organic form.

When phosphorus is released from soil minerals, organic matter or applied fertilizers, it may combine readily with calcium, magnesium, iron, manganese, aluminum or organic matter, or it may be assimilated by microorganisms or adsorbed by the silicate clay colloids. All of these processes or reactions result in the fixation of phosphorus. Fixation is beneficial in that fixed phosphorus does not leach through the soil. On the other hand, fixation has a detrimental effect inasmuch as fixed phosphorus is not readily available to plants. The total phosphorus content of soil is approximately 1500 ppm, but the concentration in the soil solution is usually less than 0.1 ppm so that only a small fraction is readily available to plants. Plants absorb phosphorus as phosphate ions ($HPO_4^{=}$ or $H_2PO_4^{-}$). Figure 22 illustrates the transformation processes and reactions which occur with phosphorus in soil.

Phosphorus is mostly available in the soil pH range between 5.5 and 7. In acid soils, phosphate reacts with iron, manganese and aluminum to form rather insoluble compounds, while in alkaline or calcareous soils (above pH 7) phosphate reacts with calcium or magnesium to also form insoluble phosphate compounds. However in Ontario soils, plant available phosphorus is present in quantities to adequately supply plants at soil pH values as high as 8. Even within the favorable pH range between 5.5 and 7, phosphate from phosphorus fertilizers reacts to form less soluble compounds and the rate of reaction and decrease in availability is minimized.

Phosphorus fertilizers are manufactured from mined deposits of minerals containing phosphorus which were laid down millions of years ago by shell-forming organisms in the ocean. The deposits currently being mined are commonly referred to as rock phosphate but consist of a carbonate fluoroapatite called francolite. The rock phosphate is treated with sulfuric acid or phosphoric acid to produce commercial phosphorus fertilizers. The major deposits of rock phosphate in North America are in Florida, Tennessee, North Carolina and several western states.

Potassium – Most soils contain between 0.5 and 2.5% potassium in combination with many other elements and compounds. The precise biochemical function of potassium in plants is unknown although it is involved in some enzymatic reactions. It is required for growth and increases disease resistance, strengthens stalks of grain plants, and increases the winter-hardiness of perennial stands of legumes. Potassium deficiencies in corn leaf and ear are shown in Figure 21.

Soil potassium can be classified into four forms listed in order of increasing availability to plants.

1. Mineral: (500 to 2500 ppm) occurs in feldspars and micas
2. "Difficulty available": (50 to 750 ppm) occurs in illite, vermiculite and chlorite-clay minerals
3. Exchangeable: (40 to 600 ppm) held by electrostatic forces on clay and organic matter surfaces
4. Solution: (1 to 10 ppm) in soil solution

While there is transformation of potassium from one form to another, the rate of transformation between the mineral and more available forms is very slow.Thus potassium in the mineral form is considered to be unavailable. "Difficulty available" or fixed potassium equilibrates slowly with the exchangeable and solution forms. Potassium in the exchangeable and solution forms equilibrates very rapidly.

Plants absorb potassium in the ionic form from the soil solution. When the concentration of potassium in the soil solution decreases because of plant removal or leaching, some potassium from the exchangeable form replenishes the quantity in the soluble form. The reverse occurs when

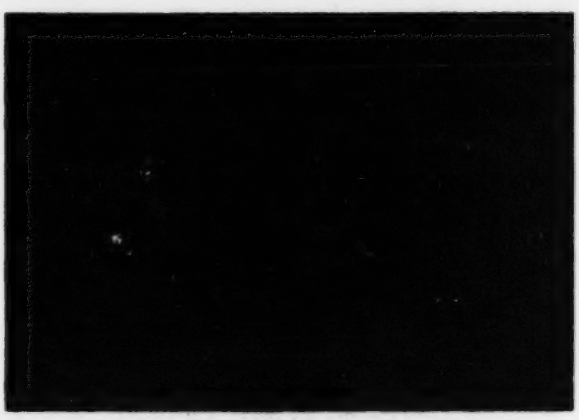

Figure 26. Zinc deficiency in corn.

soluble potassium fertilizer is added to the soil. Hence, exchangeable potassium is considered readily available.

Calcium – This is a constituent of many rocks and minerals, especially limestone. Most soils in Ontario are adequately supplied with calcium for plant growth. However, when the soil pH is low, finely ground limestone may be added to raise the pH to a satisfactory level for a crop such as alfalfa. Calcium is required by plants principally for cell wall synthesis.

Magnesium – The availability of magnesium in most Ontario soils is generally considered to be adequate for plant growth. However, there are instances where crops may contain sufficient magnesium for plant growth but insufficient quantities to fully supply the requirements of ruminant animals. Such animals suffer from hypomagnesemia. Application of too much potassium fertilizer applied over a number of years may induce magnesium deficiency in plants.

The primary sources of magnesium are dolomite (calcium-magnesium carbonate) or dolomitic limestone as well as other rocks and minerals. These may be used to overcome deficiencies in soil.

Magnesium functions as a co-factor in some plant enzymes and is also a constituent of chlorophyll in plants (Figure 23).

Sulfur – There are a number of rocks and minerals in soils which slowly release sulfur as they weather. Fertilizer materials such as ordinary superphosphate and animal wastes provide sulfur for plant growth. In some areas of Ontario, particularly near industries, a considerable amount of sulfur is returned to soil in the form of sulfur dioxide. In addition to absorbing sulfate from soil, plants absorb sulfur dioxide directly from the atmosphere.

Micronutrients

The micronutrients – boron, copper, iron, manganese, molybdenum, zinc and chlorine – are as essential for plant growth as the macronutrients, but in much smaller amounts. The range between beneficial and harmful amounts is very narrow for some of these micronutrients, and for this reason they should be used carefully as fertilizers, applied only when deficiencies are known to exist, and according to precise recommendations as to amount, form, and method of application for specific crops.

Micronutrient deficiencies in soil develop generally in a similar manner as for macronutrients, that is, by conversion to less available forms – leaching, erosion and crop removal. Ordinarily, micronutrients are not present in commercial fertilizers except as impurities. However, fertilizers which contain one or more micronutrients may be obtained by special arrangement with some fertilizer manufacturers.

The function of micronutrients in plant growth are not fully known. The following summarizes the available information on function, deficiency symptoms and methods for correction of deficiencies.

Boron – Although the exact functions of boron in plants are unknown, it is thought to be involved with sugar transport and lignification of cell walls. A definite relationship between calcium and boron exists such that as the supply of calcium to the plant is increased, boron deficiency symptoms increase or boron toxicity symptoms decrease. Potassium may lessen boron deficiency symptoms by inhibiting calcium uptake. Deficiency symptoms include a dying of growing tips (e.g, the "rosetting" in alfalfa) (Figure 24), cracked stem or "cat scratches" in celery, brown heart in turnips and sugarbeets, and internal cork of apples. Boron fertilizers may be applied directly to the soil or sprayed on the crop.

Copper – For chlorophyll formation and as a component of some enzymes in plants copper is essential. Deficiency symptoms vary considerably. Copper deficiency seldom occurs in plants growing on mineral soils in Ontario, but may be present occasionally on plants grown on organic soils. In some instances the application of copper salts to organic soils has resulted in yield increases for onions, spinach, and carrots.

Normal plant tissue may contain insufficient copper for animal requirements and thus copper must be included in the mineral component of the animal's diet.

Copper may inadvertently be applied to land in large quantities as sewage sludge. If large quantities of sludge are applied, plant growth may be inhibited. There is no evidence that humans are adversely affected by ingestion of copper in amounts somewhat greater than normal.

Iron – Most soils contain an abundance of iron and a sufficient quantity is usually available to supply plant requirements. Occasionally an iron deficiency may occur on a high-lime soil. This causes leaf chlorosis of the younger leaves, that is, the tissues between the veins contain much less chlorophyll than does a normal leaf and consequently are much lighter in color.

Manganese – The availability of manganese decreases as the soil pH increases. Deficiencies can occur in some Ontario soils with a soil pH greater than 6.0. Plants grown on organic soils or mineral soils high in organic matter are more likely to be deficient. In oats, wheat or barley, manganese deficiency causes "gray speck" or oval shaped spots on the lower part of new leaves (Figures 25). A manganese deficiency in soybeans is identifiable by whitish leaves with green veins usually on the top half of the plant. The best method for overcoming manganese deficiency is to spray the plants with a manganese sulfate solution.

Molybdenum – This element is required by plants and microorganisms in very small quantities It has been reported that the application of one ounce of molybdenum per acre would be sufficient for most crops for several years. A deficiency of molybdenum in cauliflower and broccoli causes "whip tail", a condition where patches of leaf tissue along the midrib die or fail to form while the leaf continues to elongate and twist. Molybdenum is an important component of nitrate reductase, an enzyme required for nitrate utilization by plants. It is also required for the symbiotic nitrogen fixation by Rhizobium bacteria in nodules on legume plant roots. Molybdenum deficiency rarely occurs in Ontario soils.

Zinc – This element is required for the activity of many enzymes in plants. A relationship between zinc and a plant hormone, auxin, has been observed. Chlorosis of the interveinal tissue is the most commonly reported symptom of zinc deficiency (Figure 26). With extreme deficiencies in corn, the emerging leaves are a light yellow or white. A deficiency occurs occasionally in some Ontario soils and may be induced by the application of too much phosphorus fertilizer especially on neutral or alkaline soils. Deficiencies are corrected by adding soluble zinc compounds to the soil or by spraying the foliage with solutions containing zinc. Application of too much zinc to a soil, such as repeated applications of sewage sludges, may depress plant growth.

Chlorine – In the chloride form, chlorine has recently been shown to be an essential element for the growth of higher plants although its function is unknown. However, it is not observed to be deficient in Ontario soils.

Nonessential Elements

Soils contain other elements which are not essential for the growth of the plant. These elements may be derived from one or more of the following sources:

1. rocks and minerals from which the soil was formed
2. impurities in fertilizers and lime or constituents of pesticides, manure, and sewage sludge
3. industrial and mining wastes, fossil fuel combustion products, meteoric and volcanic action
4. water or wind eroded particles or from water itself

Plants can mature quite normally and yet contain insufficient supplies of cobalt, chromium, copper, manganese, selenium and zinc for animal requirements. Other plants may grow normally but contain toxic levels for animals of selenium, cadmium, molybdenum or lead. Plants tend to exclude antimony, arsenic, berylium, chromium, titanium, vanadium, zirconium and others by only minimal absorption from soil. Absorption of many of these elements in excessive amounts may well be toxic to the plant itself. Three elements of greatest concern are lead, mercury and cadmium.

Lead – Most lead ingested by humans is deposited in bones but, if present in excess, it may affect the central nervous system producing irreversible brain damage, especially in children. Direct sources are lead-containing paints and high lead-glazed pottery. Combustion products of leaded gasoline from motor vehicles form another source. Such atmospheric lead may directly contaminate plants or end up in the soil. Lead reacts with soil organic matter and forms insoluble compounds reducing its availability to plants. Also, while plants may absorb lead into their root system, only a small portion of this lead is translocated to the top of the plant. It has been estimated that, near highways, 30 to 50% of the lead in plant tops is absorbed from the atmosphere.

Mercury – Although toxic, inorganic mercury does not cause irreversible damage except in abnormally high doses. Some organic mercury compounds such as those which are used to treat cereal grains are quite toxic. However, plants grown from treated seed do not contain appreciable amounts of mercury. Ingestion of toxic amounts of mercury causes progressive weakening of muscles, loss of coordination, constricted vision or blindness, deafness, and permanent mental retardation. Mercury reacts with soil organic matter to form rather stable organic compounds, and with various anions to form insoluble inorganic compounds. Both processes reduce its availability to plants. However, plants may absorb mercury either from the soil or from the atmosphere, and it is readily translocated from one part of the plant to another.

Cadmium – Mammals tend to accumulate cadmium and it may replace zinc in certain enzyme systems. The effects of cadmium toxicity are not clear, but hypertension and cardiovascular disease incidence have been related to high amounts of this element in animals and humans. Cadmium is easily absorbed by roots and translocated in food crop plants, especially grain. However, cadmium may also be absorbed from the atmosphere. Again, near highways, 30 to 50% of the cadmium in plants is absorbed from the atmosphere.

Soil pH is important in determining the availability of heavy metals including, lead, mercury and cadmium. In general, the pH should exceed 6.5 in order to minimize potential toxicity problems. Liming of an acid soil will decrease the availability of most heavy metals.

SOIL MANAGEMENT

Fertilizing for Crop Production

Fertilizers are one of the major costs of crop production, and Ontario farmers apply 900,000 tons of fertilizers each year. The most intensive use of fertilizers occurs where cash crops such as tobacco, vegetables and corn are grown. Some intensive livestock farms do not require purchased fertilizers.

Measurement of Fertilizer Requirements

It is possible to measure or estimate the amount of nutrients removed from the soil by a crop and to replace this with added fertilizer. This procedure is rarely satisfactory as it disregards the soil as a continuing supply of nutrients, its ability to fix nutrients in unavailable form, and losses of nutrients from the soil by leaching and volatilization. When crops are fertilized for greatest profit it is necessary in some cases to add considerably more, and in other cases considerably less nutrients in fertilizer than the crops remove.

Ontario soils vary in their content of available plant nutrients because of inherent differences in the soils and differences in past fertilization. Fertilizer requirements for a particular crop on any one field can best be determined by measuring available nutrients in the soil using chemical soil tests, or by measuring the nutrient content of the crop grown in that particular field.

In Ontario, soil tests are usually recommended as the basis for fertilizer recommendations, which are used to estimate the amounts of phosphorus, potassium, magnesium and lime required to give the most economical yield for a particular crop. Soil testing cannot correct unsatisfactory yields caused by poor crop stands, competition from weeds, planting too late or too early, poor drainage, poor physical condition of the soil (tilth), diseases, insects or unsuitable varieties. It also cannot determine the value of the land, or guarantee the same effect of fertilizers on yield and quality under all weather conditions. Since weather cannot be predicted in advance, the profit from fertilization will vary from year to year.

Plant analyses are commonly used for tree fruits and for particular problems with other crops.

Preparing a Good Fertilizer Program

The person who takes the soil sample should make certain that the sample adequately represents the field. This may be done by taking several samples mixing them thoroughly and taking a composite portion of this for analysis. Two or more composite samples of the same field are necessary where there are areas large enough to warrant separate fertilizer applications such as:

- areas where yields are lower or soils appear different from the rest of the field
- areas which have been fertilized, limed, or manured differently from the rest of the field

One should avoid sampling:

- on area where there has been a pile of manure, straw or other residues
- strike-out or dead furrow areas
- the part of the field near a heavily traveled gravel road

These areas often have higher pH values due to the addition of lime.

Time of Sampling

Sampling may be done at any convenient time. Most farmers prefer fall sampling for spring-sown crops. Samples should be sent to the laboratory as soon as possible after being taken.

Frequency of Sampling

Each field should be sampled at least once every three years. On sandy soils potassium values can change quickly where the entire crop (for example, alfalfa, hay or silage corn) is removed, and residues or manures are not returned. Under these conditions samples should be taken each year.

Fertilizer requirements indicated on the soil test report are for specific crops and management. If the crop management is changed from that on the information form submitted, the fertilizer requirement is likely to change. However, a new fertilizer recommendation can be obtained using the original soil test report from your extension specialist without resampling the field.

Time Required for a Laboratory Report

Within two weeks from the date of receiving the soil samples in the laboratory at the University of Guelph, reports will be sent to the extension specialist of the Ontario Ministry of Agriculture and Food in your county or district.

Sample boxes and information forms may be obtained from any county office of the Ontario Ministry of Agriculture and Food or from the Department of Land Resource Science, University of Guelph, Guelph, Ontario, N1G 2W1.

Plant Analyses

Leaf samples for fruit trees are analyzed for a fee by the Horticultural Research Institute of Ontario, Vineland Station. Leaf samples for other crops and organic materials such as manures are analyzed for a fee by the Department of Land Resource Science, University of Guelph. Sampling instructions and other information about these services may be obtained from the nearest county or district office of the Ontario Ministry of Agriculture and Food.

Fertilizers

The information printed on a bag of fertilizer indicates the analysis or grade, the name and address of the manufacturer, the company's brand name for the fertilizer, the registration number, the weight and the guaranteed minimum analysis (Figure 27). Some fertilizers contain micronutrients, such as boron, and this would appear as borated granular fertilizer. While not required by law, some companies may list the content of calcium, magnesium and sulfur.

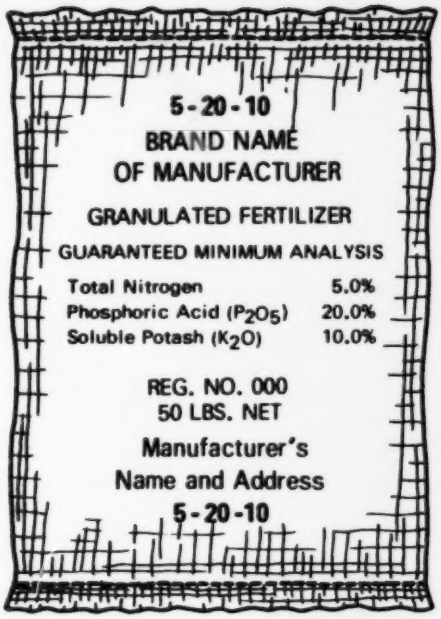

Figure 27. An illustration of the type of information normally given on a bag of fertilizer.

Fertilizer Materials

Nitrogen

Nitrogen fertilizer materials are available in dry or liquid forms. Although there are some limitations to the use of these materials, in most cases the different sources will produce similar yields. For field crops, a farmer's choice of materials should therefore depend on availability, equipment for handling, and cost per pound of nitrogen, plus the cost of application. Some common forms are described below.

Gas:

Anhydrous ammonia (NH_3), 82% N (Figure 28)
- a colorless, inflammable, irritating (to eyes, nose, throat, lungs) gas
- stored in pressure tanks, liquid under high pressure
- injected or knifed into soil during application
- should be used with extreme caution

Figure 28. Injecting anhydrous ammonia as a side-dressing for corn.

Liquid:

1. Aqua ammonia ($NH_3.H_20$), 20% N
   - ammonia dissolved in water and kept under low pressure in tanks
   - injected or knifed into soil during application
2. Nitrogen solutions, 28 to 41% N
   - 28 to 32% N materials are made by dissolving urea and ammonium nitrate in water
   - dribbled or sprayed on soil
   - 41% N solution is maintained under low pressure
   - contains ammonia, urea and ammonium nitrate
   - usually applied as a liquid knifed into the soil

Solid:

1. Urea ($CO(NH_2)_2$), 46% N
   - white, prilled (2 mm spheres), free flowing
   - broadcast on surface and usually plowed or disked into soil
   - readily converted to ammonium in the soil
2. Ammonium nitrate (NH_4NO_3), 33% N
   - white, prilled (2 mm spheres), free flowing
   - half of nitrogen in ammonium form and half in nitrate form
   - broadcast on surface and usually plowed or disked into soil

Phosphorus:

1. Ordinary superphosphate
   - consists of 18 to 20% P_2O_5 or 8.7% P in available form
   - made by treatment of rock phosphate with sulfuric acid
   - contains about 48% calcium sulfate (gypsum)
2. Concentrated or triple superphosphate
   - consists of 44 to 46% P_2O_5 or 20.1% P in available form
   - made by treatment of rock phosphate with phosphoric acid
3. Ammonium phosphates
   - produced by ammoniation of phosphoric acid
   - considerable range in phosphate and ammonium contents

Potash:

1. Potassium chloride (KC1); 60% K_2O or 50% K
   - commonly known as muriate of potash
   - most common potassium fertilizer
   - applied directly or in mixtures with other fertilizer materials
2. Potassium sulfate (K_2SO_4); 50% K_2O or 41% K
   - used for crops in which quality is adversely affected by chloride (e.g. tobacco)

In the analyses of fertilizers and soil, the term "potash" refers to the oxide form of potassium, K_2O. The potassium content of fertilizer is expressed on a K_2O basis. The term "phosphate" refers to the oxide form of P (P_2O_5) and is expressed on that basis.

Methods of Fertilizer Application

The different field, vegetable, fruit and ornamental crops grown in Ontario require a variety of fertilizer application methods. There are some general principles, however, which affect the choice of application method for most crops.

Phosphorus is rather immobile in the soil and appears to be required in larger concentrations by younger plants than by older plants. It is also less available to plants when soils are cool as they are in early spring. For these reasons, where phosphorus fertilizers are needed, it is a recommended practice for most field crops to place some phosphorus in a band with or near the seeds at the time of seeding to provide for rapid early growth. A small amount of ammonium nitrogen applied with the phosphorus increases uptake of the phosphorus.

Potassium is more mobile than phosphorus and for this reason placement with or near the seed is not as critical. Placement of some potassium with or near the seeds at seeding time is recommended on soils low in potassium.

Part of the phosphorus fertilizer and part or all of the potash may be broadcast for annual crops. However, it should be incorporated in the soil before seeding to insure that it is in the root zone. Nitrogen is quite mobile in the soil and may be applied broadcast and left on the soil surface or incorporated. For perennial crops all three nutrients are usually broadcast and left on the soil surface.

Foliar applications of nitrogen, phosphorus and potassium are not recommended as insufficient amounts can be applied in any one application. Foliar applications are quite satisfactory for most of the micronutrients.

Safe Rates of Fertilizer Application for Field Crops at Seeding

Fertilizers are toxic to plant roots and germinating seeds when applied at high concentrations, and for this reason considerable caution should be used when fertilizer is concentrated in bands with or near seeds or roots.

Fertilizer toxicity varies widely depending on the amount of soil moisture, and the degree of contact of the seed with soil moisture. To insure completely safe rates of banded fertilizer for all seeding conditions would require extremely low rates of application. The maximum safe rates suggested here will probably reduce or delay germination or retard growth appreciably in 10% of the cases where they are used.

Spring seeded oats or barley –
Fertilizer with the seed

Sands and sandy loam soils

– 30 lb nitrogen or 50 lb nitrogen + potash / acre (33 kg nitrogen or 56 kg nitrogen + potash / ha)

Loams, silt or clay loams

– 40 lb nitrogen or 60 lb nitrogen + potash / acre (45 kg nitrogen or 67 kg nitrogen + potash / ha)

All Soils

– not over 10 lb/acre (11 kg/ha) urea nitrogen should be used; and if urea is used not over 20 lb total nitrogen / acre (22 kg/ha).

Fall seeded wheat or barley –
Fertilizer with seed

All Soils

– 15 lb nitrogen or 30 lb nitrogen + potash / acre (16 kg nitrogen or 33 kg nitrogen + potash / ha). Do not use urea or diammonium phosphate (18-46-0) with fall-seeded cereals.

Corn – Fertilizer with seed

All Soils

– 6 lb nitrogen + potash per acre in 38-inch rows (6.5 kg nitrogen plus potash per hectare in 95-centimetre rows). At row widths other than 38 inches (95 centimetres) the rate may be adjusted to provide the same maximum concentration in the row. Do not use urea or diammonium phosphate (18-46-0) with the seed of corn.

Corn – Fertilizer banded

– 2 inches (5 cm) to the side and 2 inches (5 cm) below the seed.

All Soils

– 50 lb nitrogen or 80 lb nitrogen + potash / acre (56 kg nitrogen or 90 kg nitrogen + potash / hectare): not over 25 lb (28 kg) urea nitrogen. At row widths other than 38 inches (95 centimetres) the rate may be adjusted to provide the same maximum concentration in the row.

Flax and rape – No fertilizer with seed

Rates recommended are normally safe when broadcast or drilled one inch (2.5 cm) below the seed.

Peas, beans and soybeans –
No fertilizer with seed

Rates recommended are normally safe when broadcast or banded two inches (5 cm) to the side, two inches (5 cm) below the seed.

Toxicity of Common Fertilizer Materials

Nitrogen Fertilizers

Ammonium nitrate, monoammonium phosphate (12.5-50-0 or 13-52-0), and ammonium sulfate are similar in toxicity and much safer than anhydrous ammonia, aqua ammonia, or urea.

Diammonium phosphate (18-46-0) is more toxic than monoammonium phosphate (12.5-50-0) and more care should be taken, particularly with sensitive seeds and on coarse-textured (sand and sandy loam) soils than is required with ammonium nitrate or monoammonium phosphate.

Anhydrous ammonia, aqua ammonia and urea are extremely toxic fertilizers and should not be banded with or near seeds. Urea is safe when applied broadcast at or near planting time at rates normally used.

Phosphate Fertilizers

Most common phosphate fertilizers are not very toxic to seeds and plants, and no limit is normally set for the safe

rate which may be applied with or near the seed of field crops.

Diammonium phosphate (18-46-0) is more toxic than other phosphate fertilizers (see nitrogen fertilizers).

Potassium Fertilizers

Potassium chloride (KCl), the most common source of potassium in fertilizers, is somewhat less toxic per unit weight of plant nutrients than most nitrogen fertilizers.

Potassium sulfate (K_2SO_4) is less toxic than potassium chloride.

Sulfate of potash magnesia has approximately the same toxicity per unit of potassium as potassium chloride.

Potassium nitrate is one of the safer sources of potassium when considered as a nitrogen source as well.

Time of Fertilizer Application

Nitrogen fertilizers, once in the soil can convert to the nitrate form which is readily lost by leaching or under waterlogged conditions, by denitrification. In order to keep nitrogen losses to a minimum, nitrogen fertilizers should be applied as near to the time when they are required by the crop as is practical. For most spring seeded crops requiring low rates of nitrogen (less than 40 to 50 lb/acre (45 to 56 kg/ha)) it is usually recommended that all the nitrogen be applied before seeding. Application of most of the nitrogen after seeding is recommended for some crops requiring higher rates of application such as corn. In southwestern Ontario more nitrogen is required for corn if applied preplant than if applied later, probably due to losses with the early applications.

For forage grasses, three nitrogen applications per year are recommended, spaced from early spring to early fall. A similar pattern is suggested for lawns and turf. In some cases less frequent application of slow-release nitrogen fertilizer is practiced. Slow-release materials, with the exception of manure, are too expensive to be practical for most field crops.

Phosphorus and potassium fertilizers for annual crops are usually applied at or before seeding to permit incorporation in the soil. Fall application of the potassium and most of the phosphorus is also recommended. Spring and fall applications are both recommended for perennial crops. In the case of perennial forage legumes, late summer application is specifically recommended as potassium appears to be particularly important for winter hardiness of these species. Spring applications alone do not provide for high concentrations of potassium in the plant tissue in the fall if large amounts of crop material are removed in the summer.

The Economics of Fertilizer Use

In most cases the aim in applying fertilizer is to achieve the maximum profit per acre over a period of years.

If we plot crop value in bushels or dollars per acre against fertilizer application rates (Figure 29), the profit per acre is the difference between crop value and fertilizer plus non-fertilizer costs. With fertilizer use on a soil requiring fertilizer, we usually expect a rapid increase in yield, or crop value, from the first few pounds of applied fertilizer but a smaller increase in yield, or crop value, from each additional increment of applied fertilizer. In other words the more fertilizer we apply the less yield (or value) increase we expect from each individual pound applied.

The most profitable rate of fertilizer application is that at which the last pound of fertilizer applied increases the crop value just sufficiently to pay for the pound of fertilizer (point P in Figure 29). At this rate of application all previous pounds of fertilizer applied were more than paid for by increased yield or crop value. On low value crops the most profitable rate of fertilizer may be considerably less than the rate required to produce maximum yield. On very high value crops such as tobacco the most profitable rate of fertilizer is probably also the rate that provides for maximum yield, or very nearly so.

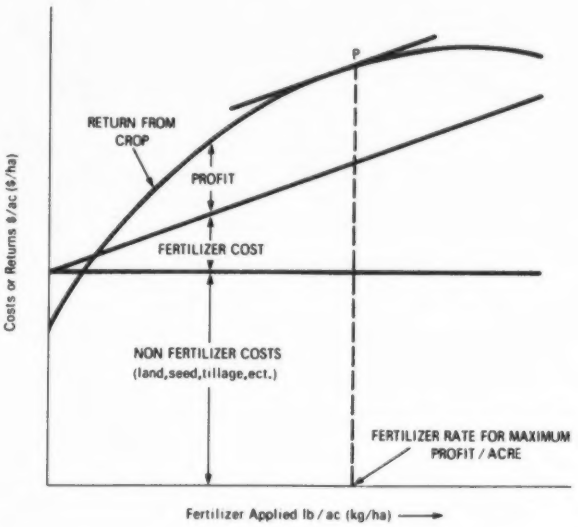

Figure 29. The economics of fertilizer use.

Different response patterns and hence different optimum rates of fertilizer application can be expected for various crops, management systems and soil test levels in the case of phosphorus, potassium and magnesium.

Soil Acidity and Liming

The Importance of pH in Soils

The solubility of such elements as iron, manganese, aluminum, zinc, copper and boron increases as the soil becomes more acidic. All of these except aluminum are essential to plant growth, but they are required in trace amounts only. In excess they may be toxic and result in reduced crop yields. Aluminum is not needed for plant growth but is quite toxic to plants. An increase in soil acidity decreases the solubility of molybdenum, an essential element for plant growth. When soil is made less acidic (more alkaline) by liming, the solubility of these elements is reversed.

Soil pH affects crops in various other ways. Legumes, such as alfalfa, trefoil, clovers and soybeans, have bacteria living in nodules on their roots which take nitrogen from the air and fix in a form which plants can use. The bacteria thrive best at pH values above 6.0 in Ontario soils. Hence a pH above this value is best for legume crops. Potato scab is more prevalent at soil pH values above 5.5 than at lower

values, although potato plants grow well at higher pH values. Some plants such as rhododendrons and blueberries grow well only at pH values below 6.0 and appear to suffer from iron and/or manganese deficiencies at higher pH values. There is also evidence that fungi associated with healthy root development on these plants also require a low pH. On the other hand, most field crops grow best in the pH range of 5.5 to 8.0. In many soils aluminum and/or manganese are at toxic levels for common field crops at soil pH values below 5.5.

In most cases where southern Ontario soils are acidic, the depth of acidity in the soil profile extends only to 18 to 24 inches (45 to 60 cm).

Reducing Soil pH

In the presence of free limestone or dolomite, soil pH may reach 8.4. The reduction of soil pH is not practical or necessary in Ontario for the production of most farm crops but is practiced on a small scale for some ornamental plants, such as azalea and rhododendron. The chemicals used to lower soil pH are sulfur and aluminum or iron sulfates. The amount required can be calculated from the results of soil analyses.

Effect of Fertilizers on Soil pH

Ammonium nitrate, urea, anhydrous ammonia and nitrogen solutions all have the same acidifying effect per pound of nitrogen used. Sulfate of ammonia and ammonium phosphate have an acidifying effect about three times greater than the above. The reduction of soil pH, due to nitrogen fertilization, occurs gradually year by year. Anhydrous ammonia, aqua ammonia and urea can cause temporary but marked pH increases when they are first applied. Other fertilizer materials such as superphosphates, and sulfate of potash have little effect on pH.

Although different fertilizers vary in their effect on soil pH under Ontario conditions, this is rarely of sufficient importance to justify a change of fertilizer material. Excessive use of nitrogen fertilizers increases the need for lime.

On soils of loam, silt loam or clay loam texture, with a pH value above 7.0, intensive nitrogen fertilizer use probably will not have any great effect on soil pH for many years to come. Soils with pH values below 7.0 have their pH reduced more rapidly by continued use of high rates of nitrogen fertilizers. The effect of nitrogen fertilizer on pH is most marked on sandy soils low in organic matter.

There have been frequent occurrences of very low pH areas in fields where the average pH indicates no lime required. These areas usually occur where there are coarse-textured (sandy) areas in a field that is predominantly medium textured. They are usually associated with high nitrogen fertilization.

Correction of Soil Acidity

Applying ground limestone is the least expensive way to correct soil acidity. There are two major types of limestone available for this purpose: calcitic and dolomitic.

Calcitic limestone is almost pure calcium carbonate. Dolomitic limestone contains considerable magnesium and is a good source of this element for acid soils deficient in magnesium. Calcitic limestone is slightly more soluble in the soil than dolomitic limestone. However, the total neutralizing value of dolomitic limestone is slightly higher than that of calcitic. Dolomitic limestone is recommended in Ontario where the soil test for magnesium is 100 or below, but either source of lime may be used if the test for magnesium is above 100.

How Limestone Should be Applied to Soil

Limestone should be applied evenly and worked into the soil by plowing or disking. Lime is not effective unless it is mixed with the soil.

Rates of Application of Agricultural Limestone

The amount of limestone required will depend upon:

1. Soil acidity – the more acid the soil the more lime is needed.
2. Soil texture and organic matter – the finer the texture and the more organic matter present, the more lime is required at any given pH value.
3. Crop – some crops require higher soil pH than others.
4. Liming materials – the greater the neutralizing value of the liming material, the less is required.

Fine particles are faster acting than coarse particles, and calcitic limestone is faster acting than dolomitic. However, for particle sizes within the recommended range, and for both types of limestone, the result will be similar over a period of two to three years.

Table 13 shows the recommended rates of application for most crops. At pH values above 6.0 no lime is required.

Table 13. Ground limestone required to correct soil pH for some common crops

Crop	Fine-textured and organic soils			Medium and coarse-textured soils		
	pH values			pH values		
	4.5-5.0	5.1-5.5	5.6-6.0	4.5-5.0	5.1-5.5	5.6-6.0
	Short ton/acre (Metric ton/ha)					
Legume forages, small grains, soybeans	4 (8)	3 (6)	2 (4)	3 (6)	2 (4)	1 (2)
Corn	4 (8)	2 (4)	0	3 (6)	2 (4)	0
Vegetables	4 (8)	3 (6)	2 (4)	3 (6)	2 (4)	1 (2)
Potatoes	at pH below 4.5 use 2 (4) tons on organic soils and 1 - 3 (2 - 4) tons on medium or coarse-textured soils.					

Soil Tilth and Tillage

Experience has taught that a certain amount of soil tillage is required for crop production. Besides controlling weeds and incorporating crop residues, soil tillage provides a seedbed and an environment suitable for plant root growth.

Soil Tilth

The word "tilth" is frequently used to describe the suitability of a soil for the germination and growth of specific seeds. A fine tilth is required for small seeds, such as grass, whereas a coarser tilth is suitable for the larger seeds, such as beans and corn. Tilth describes soil structure in terms of the size-distribution of the soil aggregates and their resistance to breakdown by tillage and rainfall.

The preferred sizes of aggregates range from 1 to 5 millimetres. A soil with large and stable aggregates has large stable soil pores which, ideally, extend from the surface to the water table or tile drains. Such pores ensure a rapid intake of water at the soil surface, and facilitate the natural drainage of excess water. Moisture for plant use is stored in the pores, which are distributed throughout the soil, and within the soil aggregate itself. This moisture is not removed by gravitational forces during drainage.

It is essential that the individual aggregates maintain their stability for several weeks after the seeds are planted. If the aggregates disintegrate after wetting and drying, a crust may form on the soil surface. Firm and thick crusts impede the entry of water, may restrict soil aeration and reduce seedling emergence.

When a soil is in good tilth, there is close contact between the seed and the aggregate, permitting moisture to move into the seed and start germination. That is why farmers prepare a fine, firm seedbed, use press wheels on various planters, or compact the soil by different kinds of land rollers, particularly after planting spring grain underseeded with a grass-legume mixture. It must be recognized that only the volume of soil extending an inch or so away from the seeds affects the movement of moisture to the seeds. The soil between the rows is not part of the seedbed and accordingly should be left loose to facilitate water entry and aeration.

Tillage

Tillage refers to the physical manipulation of soil to change its structure, incorporate residues, fertilizers and amendments, or control weed growth. It exerts a major influence on water intake, storage and evaporation from soil and on germination of seeds, root development and water extraction by plants. Consequently, tillage is an important management factor for food and fiber production and control of sediment and nutrient losses from cropland.

Tillage benefits water intake and storage by establishing a macro- and micropore distribution which maximizes water movement through large pores and water retention by small pores. This is accomplished by a loosening of undisturbed soil by tillage implements such that the majority of the aggregates lie in the range of 1 to 5 millimetre diameter. Excess tillage which reduces the aggregates to smaller sizes or primary particles is detrimental, moisture movement is hindered and rainfall may run off the surface before it can enter the soil. The larger pores formed with ideal aggregation not only allow rainfall to enter the soil, but permit drainage through the rooting zone and facilitate aeration by the drained pores.

Tillage can also control moisture loss from soil thus conserving moisture for crop growth. Loosening surface soil forms a soil mulch which interrupts capillary flow and evaporative loss of moisture from the rooting zone. Removal of unwanted living vegetation likewise conserves moisture by reducing evapotranspiration. A good seedbed can only be prepared when the soil is dry enough to be pulverized sufficiently to permit the placing and firming of seeds, so that soil moisture and air can be supplied for germination.

A recently plowed soil may require packing before planting a crop to prevent excessive moisture loss from large voids. A favorable size distribution of soil aggregates from timely tillage benefits root development as well as moisture relations. A good root system enables a crop to utilize soil moisture and nutrients most efficiently.

Primary Tillage

The moldboard plow is the most widely used implement for the primary preparation of a seedbed on Ontario farms. On a fine-textured soil or on a dense sod, the plow is the most effective and economical implement for primary tillage. Although many implements have been tried as replacements, the plow does the best job of turning under cover crops, residues and trash, and at the same time buries weed seeds and checks the growth of perennial weeds.

When adjusted and operated properly, a moldboard plow cuts, lifts, shears, and turns the furrow slice. These actions greatly improve the tilth of clay soils, provided the moisture content is right. Working clay soils when too wet results in a poor structure and may contribute to the formation of plow pans.

Fall plowing is preferred on most fine-textured soils. The large clods break into soil aggregates as a result of freezing and thawing during the winter. It is difficult and costly to prepare a good tilth if the soil is dry and cloddy. Clay soils, particularly those low in organic matter, have a very narrow moisture range when tillage is most effective.

Spring plowing is feasible on most coarse and medium-textured soils provided the seeds are planted before the soil dries out. In many cases very little supplementary tillage is required and seeding follows directly after plowing. Erosion by wind or water is substantially reduced by spring plowing as the soil is not left unprotected by vegetation for long periods.

Supplementary Tillage

The time and amount of tillage that a soil requires depend on the season, the crops that are grown and the growth habits of the weeds that must be killed or checked. Cultivation of fine-textured soils when they are too wet may induce puddling and the formation of large clods. Sandy soils are less likely to be damaged by tillage at improper soil moisture contents.

The primary purpose of supplementary tillage on plowed land is to level, pulverize, and pack the soil before seeding. Coarse and medium-textured soils seldom require more tillage than once over with a spike-toothed harrow or a double-disk harrow before seeding. If the soil is dry or if the seeds are small, a smooth or corrugated land roller may be

used after seeding to firm the soil and to ensure a better contact between seed and soil. It may be advisable to firm a sandy soil with a plow packer or roller immediately after plowing to conserve moisture. Clay soils that are plowed in the fall seldom require more than disking and harrowing to prepare the seedbed in the spring. However, if the soil is worked when too wet, several operations are required to prepare a desirable tilth. Springtoothed harrows and cultivators are used to loosen a compacted surface without disturbing the soil underneath. These implements are frequently used for after harvest cultivation to suppress weed growth.

Minimum Tillage

Minimum tillage implies soil preparation methods for planting in which the number of machine operations or trips over the field is less than with conventional methods. The additional tillage, especially disking and harrowing, does not ensure a better tilth but may shift the soil, leaving the fine aggregates deeper than the seeds. Excessive tillage leaves the tilth so fine that crusting or puddling may occur after a rain. Minimum tillage methods normally apply to the preparation of a soil for seeds of corn, beans and oats.

The principal advantages of minimum tillage are:

- a saving in labor and machinery operation
- less danger of over-tillage
- the soil between the rows is rough and porous (a condition that is conducive to maximum infiltration of water, minimum erosion, and poor germination of weed seeds)

Minimum tillage may result in low plant population and reduced yields because of:

- a moisture deficiency at the time of planting or soon after
- a soil tilth too coarse, resulting in a droughty soil
- over-compaction causing poor aeration

Deep Tillage

Excessive soil compaction restricts plant growth, water movement and soil aeration. There are three general types of soil compaction: (1) traffic pans (2) genetic pans, and (3) compacted subsoils and parent materials.

Traffic pans form in the bottom of a furrow when wet soil is compressed by plow or tractor wheels. Compaction is most likely to occur if the soil is tiled when it is too wet. Fortunately, most traffic pans in Ontario soils disappear with the freezing and thawing cycles during winter. Traffic pans that resist the frost action may be shattered by deeper plowing (once is usually enough) when soil in the pan is relatively dry and will crumble.

A genetic pan is a compacted soil layer 2 to 12 inches (5 to 30 cm) thick, that has developed naturally during the formation of the soil. In most cases, these pans may be shattered by subsoiling when the soil in the pan is relatively dry. A subsoiler is an implement equipped with a blade and shoe that cuts through the soil, lifting and disrupting the compacted layer with a minimum of disturbance to the surface soil.

In some clays, the subsoil and parent materials are so dense and compacted that drainage and aeration are impeded. Numerous experiments on such soils have shown no prolonged beneficial effect from subsoiling. The soil to the depth of the subsoil is temporarily loosened but after one or two years it will reconsolidate.

Recommendations for Tillage

On a fine-textured soil

- fall plow whenever possible
- avoid excessive secondary tillage
- avoid working when excessively wet (at or above field capacity)

On coarse-textured soil

- avoid excessive tillage
- use methods which leave residues on or near the surface, particularly sloping, erodible soils

Land Drainage

Land drainage is a special management practice that removes surplus water from the soil at certain seasons of the year and also lowers the water table. It has been estimated that 40% of the agricultural land area in southern Ontario is poorly drained and that 20% is imperfectly drained. Land drainage is a major problem in developing agricultural areas in northern Ontario. Land is drained primarily to improve agricultural productivity and increase farming efficiency by greater crop yields, wider choice of crops, and more timely tillage and harvesting operations.

Where Needed

Soil color is often a useful indication of the soil drainage conditions. A very dark surface soil is normally a reflection of poor drainage – the decomposition of organic residues is slow and incomplete due to poor aeration. A water table that is close to the surface or that fluctuates during the year results in soil horizons that are a mottled brown, yellow, or gray in color or causes a gley horizon.

The occurrence of winterkilling and heaving of fall wheat, alfalfa, and clovers is most frequent on soils where drainage is inadequate or where there are prolonged accumulations of water or ice on the soil surface.

Types of Land Drainage

Surface drainage is a method of collecting and removing excess water from the soil surface. Complementary practices, such as land leveling and plowing in narrow lands, assist in the collection of the water and its discharge into drainage ditches or grassed waterways. Surface drainage may be used in areas where soil permeability is too slow for a tile drainage system to be effective.

In the subsurface, drainage water moves through the soils into tiles made of fired clay, concrete, plastic or into perforated pipes, and is discharged into a drainage ditch or a suitable prepared outlet (Figure 30). The planning and designing of tile drainage systems require a knowledge of the permeability characteristics of the soil and crops that are to be grown.

In making a decision on a land drainage system, a farmer should consider:

- the cash value or feeding value of adaptable crops
- the soil texture (the permeability of some clay soils is so slow that a tile drainage system is not effective)

- the availability of good drainage outlets
- the proportion of good and poor land in the area to be drained
- drainage as part of a total farm management program

Some of the benefits of land drainage are that it:

- increases the number of climatically adaptable crops that may be grown
- promotes good crop quality
- lengthens growing season at the beginning for planting and at the end for harvesting
- presents fewer seedbed problems and reduces labor and machinery costs
- increases the resistance of a plant to drought by promoting deeper and more extensive rooting
- reduces the frequency of crop heaving and winterkilling
- improves soil aeration and soil structure
- promotes earlier growth (a dry soil warms up faster)
- enables farm machinery to be used more efficiently

Figure 30. Fired clay tiles are laid in the trench made by a tile machine.

Soil Erosion

Erosion

Much of the rainfall which reaches the soil surface is absorbed by the soil, but under certain conditions some of it is lost as runoff. Soil moved from its original position to a new site by this runoff constitutes soil erosion by water which consists of two processes: detachment and transport.

In order to be transported, soil particles must be detached from the larger, more stable aggregates at the original site. If this detachment did not occur, erosion would not take place, even with runoff water passing over the site.

Raindrops are the principal detaching agent, although frost, animals, etc may facilitate the process. As raindrops strike the soil surface, the soil becomes moist. and with the velocity of the drop (Figure 31) sufficient energy is transmitted to the soil surface to break stable aggregates and disperse fine particles into a water suspension. The evidence for this may be seen on the walls of nearby buildings or stems of plants.

The detachment and dispersion of particles into a suspension in water is referred to as splash erosion. Subse

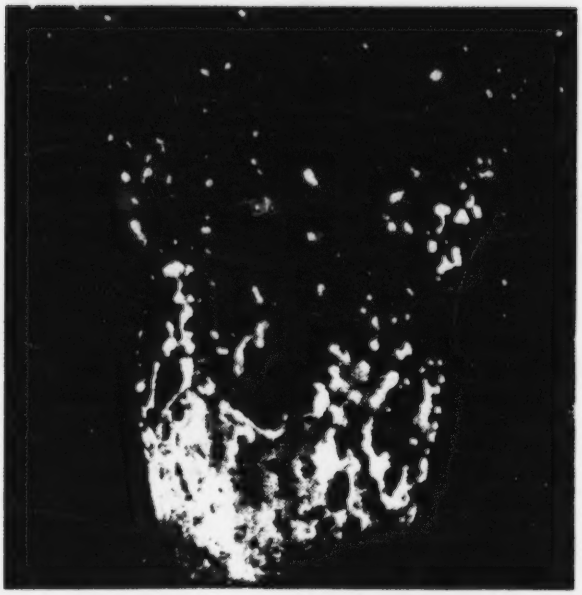

Figure 31. A raindrop hits the soil with enough energy to break a soil clod into small aggregates which are easily transported by moving water.

quently, the suspended material may be relocated in small local depressions, filling the pores of the soil surface, or move directly down any slope that exists. Filling the soil pores seals the immediate surface and slows down the infiltration of the rainfall into the soil, thus increasing the volume of runoff which can carry suspended soil particles. This movement of soil particles constitutes the transport process in erosion.

Factors Contributing to Soil Erosion by Water

Climate – Rainfall is the most important climatic factor contributing to erosion by water. Temperature also plays a part in soil erosion by determining whether precipitation falls as rain or snow, and by subjecting the soil to freezing and thawing cycles which help detach particles from aggregates and influence the infiltration capacity of the soil. Melting snow can erode sloping surface soils when there is a shallow layer of thawed soil over impermeable frozen soil because all the meltwater must runoff and the action of the frost has rendered the soil particles readily detachable. Wind influences rainfall through its driving force, altering the angle of impact with the soil surface. Wind and temperature influence evaporation of soil moisture – the moisture content of the soil at the beginning of a storm determines in part the amount of erosion which may result.

Soil – Since erosion by water depends on runoff, the permeability of the soil or its infiltration rate is an important aspect of erosion losses. Runoff occurs once the infiltration capacity has been exceeded. The other soil factor of secondary importance is the susceptibility of soil particles to be detached.

The ability of the soil to accept rainfall depends on the condition of the soil surface. If the soil is coarse-textured, the pores will be larger than in a fine-textured soil. In either case, a good structure with stable aggregates will maximize the effective pore size and benefit water movement. When

soils become dispersed, the finer particles fill the existing pores and reduce water movement to the underlying soil.

Soil moisture affects infiltration and runoff. If a soil is dry, the first part, and possibly the whole rainstorm will be used in rewetting the soil. If it is already wet, a larger portion of the storm may contribute to runoff. The permeability of the soil profile also influences moisture relations. A poorly drained soil will remain saturated at the surface longer than a well-drained one. Permeability also affects the rate of infiltration following saturation of the surface.

Topography – Flat land is not as subject to erosion as sloping land. This is especially true in summer when frost does not interfere with infiltration. On the other hand flat lands are frequently finer in texture and exhibit characteristically lower infiltration rates. They are often slowly, imperfectly, or poorly drained.

If permeability is good, permitting a high rate of infiltration, an increasing length of slope can benefit the movement of water into the soil and reduce erosion. Otherwise increasing slope length increases erosion losses. The intensity of the storm also influences the manner in which slope length affects erosion.

Vegetation – Abundant vegetation, with its canopy effect while growing and its residual debris, is the most important factor influencing the erosion which might result from certain climatic and soil situations. Vegetation acts as a physical protector, absorbing the energy of the raindrops before they reach the soil surface, and reducing the cutting action of whatever runoff may occur. Plants also hold some rainwater for direct evaporation as well as transpiring considerable moisture, all of which hastens the drying of the soil and consequently a greater rainfall requirement before reaching the stage at which it might erode in a subsequent storm.

The roots of plants exert an aggregating effect on soil particles as well as forming a physical binding in themselves. Forage crops with their grass species are particularly effective in this respect. Forage crops also occupy the soil over the whole year and protect the soil in winter as well as summer.

The management of soils for crop growth influences the vigor and consequently the effectiveness of any crop in erosion control. The management of the crop itself determines growth and duration of its presence on a given field.

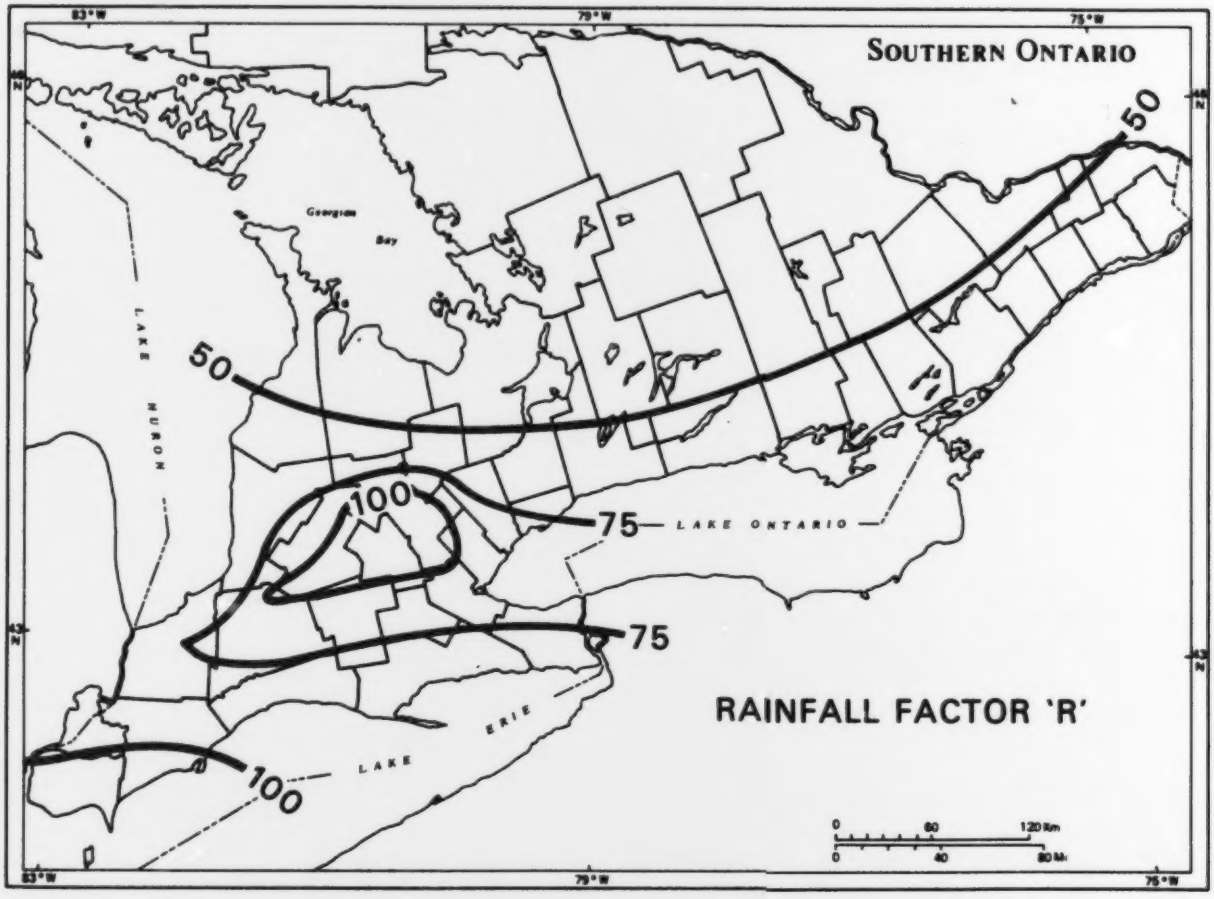

Figure 32. Average annual value of the rainfall factor "R" for southern Ontario.

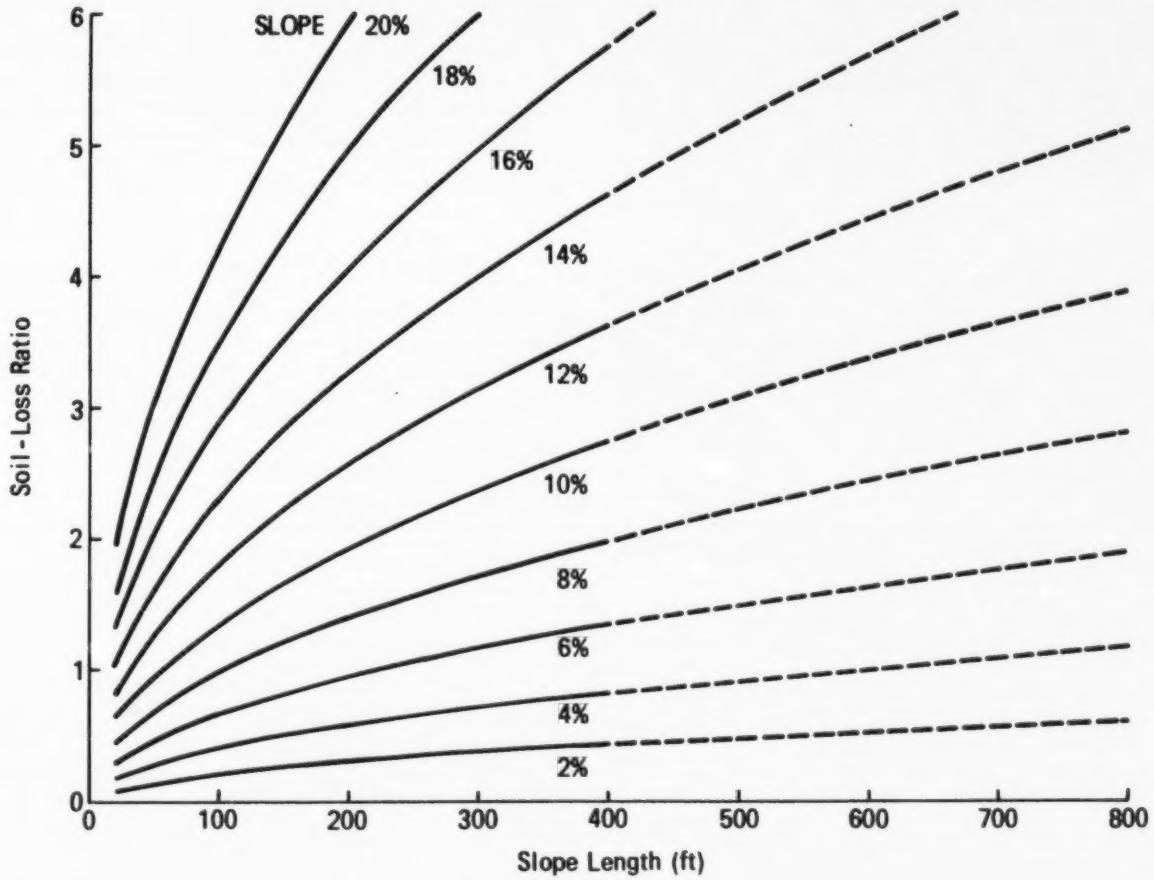

Figure 33. Soil-loss ratio for different slope lengths and gradients.

The Universal Soil Loss Equation

The above factors have been incorporated into a single equation to predict soil erosion losses[1]. The form of the equation is:

$$A = R K L S C P$$

where A = average annual soil loss in tons per acre computed for a given situation of

R = measure of the erosion potential of the average rainfall for the area, ranging from 50 to 100 depending on location in Ontario (Figure 32).

K = soil-erodibility; rate of erosion for a particular soil in tons per acre per unit erosion index from a fallow plot 72.6 ft long with 7 percent slope. In Ontario

sandy loam	=	.20
silt loam	=	.35
loam	=	.25
loamy sand	=	.10

L and S = length of slope and gradient (Figure 33)

C = crop management – the ratio of soil loss from land cropped under specific crop management to the corresponding loss from continuously fall and tilled land e.g.:

growing corn crop	=	.26
forage crop	=	.02
tobacco	=	.28
soybeans	=	.35
small grains	=	.25

P = erosion control practices e.g.:

contour farming	=	.50
strip cropping	=	.25
terracing	=	.10
no control	=	1.00

[1] *Walter H Wischmeier and Dwight D. Smith, 1965. Rainfall-erosion losses from cropland east of the Rocky Mountains. Agriculture Handbook No. 282 ARS-USDA*

Water Erosion Control

This consists essentially of manipulating the crop and controlling factors in the erosion equation to maximize these effects.

- Maintain a vigorous crop on land as much of the time as possible. Use forage crops where erosion is likely under other crops.
- Retain residues at or near the soil surface. Spring plowing should be used in preference to fall plowing on sloping land. No-till practices may be a feasible means of keeping residues on the surface of sloping fields.
- Use appropriate control practices.

Strip cropping is an erosion control measure that may be used on long, smooth slopes that are planted to grain or row crops. It consists of maintaining strips of hay alternately with strips of grain or row crops. The width of the strips varies from 60 to 150 feet (20 to 51 metres) depending on the length and steepness of the slope, the erodibility of the soil and the crop rotation. In other words, the greater the erosion hazard, the narrower the strips. In field strip cropping, the strips are straight, of uniform width, and are laid out across the general slope of the land. Field strips are recommended on uniform slopes where it would appear that no greater control of erosion would be attained by contour strips.

The advantages of strip cropping are as follows:

- reduces the velocity of the water flowing over the surface
- increases the time for water to infiltrate
- facilitates contour cultivation

Special practices to manage unavoidable runoff are:

Grass Waterways – Grass or sod waterways are specially prepared water courses that remove surplus water without causing erosion. Many open ditches or gullies that are impassable to machinery may be changed to grass waterways by reshaping and seeding to grass and legumes.

A grass waterway is a broad channel with gently sloping sides and is shaped by plowing or grading. The larger the area that is drained, the wider the waterway must be; a channel less than 20 feet (7 metres) in width is seldom recommended. After the channel has been shaped, a mulching with straw or manure and a light seeding of oats will hold the soil in place until the grass and legumes become established. Waterways should be established when the remainder of the field is in hay.

It is essential that the waterway be kept in a grass-legume mixture and harvested for hay. The strips should be fertilized regularly, not be used as lanes and not disturbed by plowing or cultivation.

Diversion ditches – Diversion ditches or diversion terraces are low embankments of soil thrown up on slopes for the purpose of diverting surface water away from the land farther down the slope. These channels, about 20 feet (7 metres) in width, are left permanently in sod regardless of the crops above or below. The sides of the ditches are gently sloped and present no difficulty in hay removal.

Three situations where diversion ditches are used:

- to break up long uniform slopes if strip cropping is not controlling erosion
- to divert water while gullies are being repaired or while grass waterways are being established
- to protect buildings or property from periodic flooding

The water from diversion ditches may be discharged into established grass waterways and from there to unpastured woodlots or into a sod field where erosion and gullying will not develop.

Gully Erosion

Gullies are formed when large volumes of water are confined to a narrow channel (Figure 34). They may develop in all types of soil but are most common in Ontario in sandy soils where intertilled crops such as corn, soybeans, or tobacco are grown. Deep gullies have formed in clay soils adjoining river channels and lakeshores.

Some of the common situations that lead to gullies being developed are:

- wheel tracks in loose soil
- dead furrows
- livestock paths
- neglected natural watercourses
- discharging water from yards or waterways onto soils without adequate plant cover

Gully erosion is seldom controlled by dumping stones, brush or old wire fencing in the channel. The water flows around the rubbish and gouges out the side, or accumulates behind an obstacle and when suddenly released, creates a worse gully. To stop gullying and allow the sides and bottom to be covered with vegetation, it is necessary to reduce the velocity of the water along the full length of the gully by one or more of the following:

- a series of check dams of logs, boards, or sandbags placed across the gully at frequent intervals
- placing 1 to 3 feet (0.3 to 1 metres) of straw in the channel and anchoring it down by brush 8 to 10 feet (3 to 3.5 metres) in length with the trunk end placed upstream.

Figure 34. Shallow gully erosion caused by one rainstorm.

Large gullies, such as occur along lakeshores, require costly remedial measures. The gully walls must be pushed in, graded, and stabilized by vegetation, stonework, or concrete structures.

Wind Erosion

In Ontario, wind erosion or soil drifting is generally a localized problem and is confined mostly to sandy, muck or peat soils. Drifting may occur on any soil if it is cultivated while very dry, as in summer fallowing.

Except for the shifting sand dunes along some lakeshores, the sandy soils now subject to wind erosion were once forested. When these soils were cleared and cultivated, the organic matter was rapidly depleted and the bare soil began drifting.

The principal means of control include the following practices:

- planting windbreaks using two or more rows of trees with different growth habits, such as Carolina poplar and white spruce
- using strips of different crops at right angles to the prevailing wind direction
- sowing cover crops of winter rye after harvesting such crops as tobacco, potatoes, or vegetables.

Large areas of drifting soil may be stabilized by planting rapidly growing trees (certain species of poplars) to afford some protection while conifers become established. "Blowouts" develop in sandy soils that have been overgrazed. A preventive measure against wind erosion is to keep the soil adequately covered with trees or grass.

Rotation of Crops

The more or less regular succession of different crops on a given area of land has been practiced by progressive farmers for many years. Growing these different crops in a regular sequence has come to be called crop rotation. Continuous cropping or monoculture refers to the growing of the same crop year after year.

In choosing a rotation for any given field or farm, the requirements of feed for livestock, the requirements for cash crop, the erosion hazards, the soil drainage characteristics, and the relative soil fertility levels must be considered.

Advantages of Rotation of Crops

1. Legumes in rotation can utilize atmospheric nitrogen and increase the nitrogen content of soil for the succeeding crop.
2. Weeds, diseases and plant insects often can be more easily controlled.
3. Higher yields per acre of crops are frequently obtained.
4. Soil erosion and nutrient losses by leaching generally are reduced.
5. A rotation including two to three years of grass-legume crop improves the structure, drainage and aeration of a clay soil, especially the cultivated layer.

The best rotation for a given farm makes the most effective use of equipment, livestock, management, labor and land to give the greatest profit from the farm over a period of years.

Choosing a Rotation

One long-term cropping system cannot generally be recommended. A specific cropping system may become obsolete because of changes in prices and costs of producing different crops, introduction of new crops or new tillage methods and insect, disease, or weed buildup.

The cropping sequence that a farmer tends to follow usually depends on:

1. The principal source of farm income, e.g. livestock, milk, grain, cash crop.
2. Soil drainage, fertility, erosion and runoff hazards.
3. Climatically adapted crops.

Soil Mulching

Mulching is a practice which involves the addition of organic matter to the surface of a soil to reduce water losses by evaporation and to suppress weed growth.

The major benefits from mulching crops, particularly certain tree fruits and landscaping plants are:

- conservation of soil moisture
- regulation of soil temperatures
- the suppression of weed growth

Various materials are used as mulches: plant residues (hay, straw, corn cobs), sawdust and wood chips. In addition to the vegetative materials such products as glass wool, cinders and plastic films have been used.

The principal disadvantage of mulching is that rodents, primarily mice, live in the mulch and cause tree damage by girdling. Rodenticides are available to reduce the mouse hazard.

LIVESTOCK AND POULTRY MANURES

There are basically two forms in which livestock manures are handled: (a) as semi-solids with bedding material, and (b) as liquids or slurries. With some poultry operations, the manure is allowed to accumulate under the rearing area and no bedding or absorbent is used.

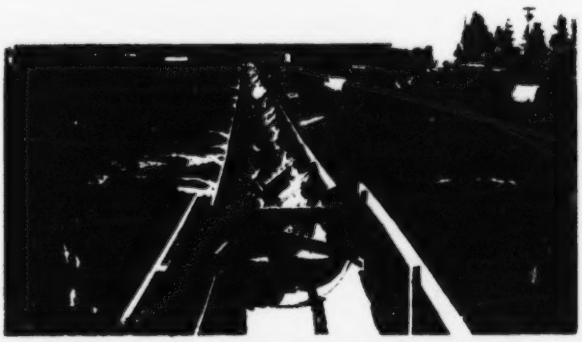

Figure 35. A large scale beef-producing operation.

Solid Manures with Bedding

In terms of numbers of operations and tonnages, most of the livestock manures in Ontario are handled as a semi-solid material with bedding. Many hog and poultry (layers and broilers) producers use a liquid or slurry system, or allow the bird droppings to accumulate in a compartment below the rearing area.

Quantities and Composition

The composition of manures in terms of nutrient elements and the quantity or volume varies with breed, age and weight, purpose or function of the animal (meat, milk, breeding stock, egg-production, broilers), and the rations that the birds or animals are fed. The data in Table 14 were accumulated from various sources.

Within southern Ontario, it has been estimated that there are more than 90 million farm animals and poultry that produce in excess of 38 million tons of manures annually[1]. In terms of animal units, the animal and poultry population represent more than 2.4 million units. The distribution of the animal units, the manure produced and its utilization in relation to crop production are discussed later.

The numbers of poultry or livestock (1000 chicken broilers, 2 beef feeders, dairy cow etc) are equivalent to one animal unit in terms of the nitrogen contained in the manure.

In addition to the elements listed in Table 14, manures contain small amounts of other elements. The high and low values for the elements are associated with various livestock or poultry (Table 15).

Table 15. Composition of manures – elements occurring in small amounts

Element	Pounds per ton	
	Low levels	High levels
Sulfur	1.0 (dairy)	2.7 (hog)
Calcium	2.4 (beef)	15.7 (horse)
Magnesium	1.6 (hog)	3.7 (sheep)
Iron	0.08 (cattle)	0.6 (hog)
Boron	0.03 (dairy)	0.12 (poultry)
Manganese	0.2 (beef)	0.7 (poultry)
Copper	0.05 (poultry)	0.4 (hog)
Zinc	0.5 (poultry)	1.5 (hog)
Nickel, lead (trace amounts)		

Conversion factor: lb/ton x 0.5 = kg/MT

1.0 lb = 0.45 kg
1.0 cu ft = 0.03 cu m

[1] *Black, S.A., J.B. Robinson and T.H. Lane. 1971. Pollution problems associated with poultry and animal wastes in the Ontario Great Lakes Basin. University of Guelph.*

Table 14. Approximate quantities and composition of poultry and livestock manures

Source Market Basis	Moisture %	Daily production lb	Daily production cu ft	Pounds produced during confinement: Nitrogen	Phosphorus	Potassium
1,000 chicken broilers or roasters (4 to 5 lb)	80	90	3	170	24	33
300 turkey broiler 11 to 12 lb	–	–	–	150	33	37
15 feeder hogs gain 40 to 200 lb	85	150	4.5	150	40	50
2 beef feeders gain 400 to 1,100 lb	85	100	1.6	175	28	110
40 veal calves gain 30 to 300 lb	–	–	–	160	40	115
Annual basis 365 days						
1 dairy cow 1,300 lb plus calf	85	100	1.6	170	35	150
125 laying hens 4 to 5 lb	80	37	0.6	175	42	54

The nitrogen component of manures is of particular interest in crop production. The amounts of nitrogen and the forms in which they occur are given in Table 16.

Table 16. The percentage distribution of ammonia and organic forms of nitrogen in manures

Form	Dairy	Beef	Hog	Poultry
Ammonia-nitrogen	62	42	68	81
Organic-nitrogen	38	58	32	19

The generalized reactions involving the principal forms of nitrogen in organic wastes have been covered in the section on Biological Properties of a Soil.

Breakdown Products in Soil

Animal rations contain carbohydrates (sugars, starch, cellulose and hemicellulose), proteins, fats and small amounts of lignin and inorganic nutrients. In concentrated rations about three-quarters of the organic nutrients, mostly carbohydrates and proteins and some inorganic elements, are utilized by the animal. About 90% of the dry matter in manures is organic material containing more lignin and minerals and less carbohydrate than the ration.

Under aerobic soil conditions most of the carbonaceous materials in the manures are oxidized to carbon dioxide, and microbial cells are synthesized, while nitrates, sulfates and inorganic phosphorus are released. The carbonaceous materials subject to decomposition include polysaccharides, cellulose, starch and most proteinaceous compounds. The lignin fraction and the protein associated with the lignin are considered to be resistant to rapid breakdown. When large quantities of organic wastes such as manures or sludges are incorporated with a soil, ammonia may accumulate to concentrations that interfere with seed germination or plant growth.

If anaerobic conditions develop in a soil, usually from poor natural soil drainage or excessive precipitation, a considerable amount of the nitrogen in manures may be lost to the atmosphere by denitrification. Organic acids and other compounds may then be generated that interfere with plant growth. Foul smelling odors, principally sulfides resulting from the decomposition of proteinaceous compounds, may develop.

For details on the products of aerobic and anaerobic decompositions, see the section on Biological Properties of a Soil.

Source of Plant Nutrients

It has been estimated that 75% or more of the organic material contained in manures will undergo microbial decomposition in the first year in a well-drained soil. The mineralization processes result in the release of numerous plant available nutrients, such as nitrogen, phosphorus, potassium and many micronutrients. Excessive applications of manures or sludges could result in a movement of the soluble nutrients to the groundwater, particularly the nitrate-nitrogen.

The amounts of nitrogen, phosphorus, and potassium in manure from different animals are given in Table 17.

More than one-half of the nitrogen and at least three-quarters of the potassium excreted by a cow is contained in the urine. Most of the phosphorus is in the feces.

The value of manure may also be calculated on the basis of its effect in increasing crop yields. The increase will vary depending on the crops grown, the fertility level of the soil, the climate, and the care with which manure is stored and handled. Results obtained from experiments on a soil give an indication of the value of manure at various rates for corn grain production (Table 18).

Table 18. The effects of various rates of beef, hog and poultry manures on the yield of corn, average for three years*

	Manure applied, ton/acre			
	0	5	10	20
Source of manure	Yield, bu/acre			
Beef	75	93	97	106
Swine	75	94	108	123
Poultry	75	114	129	124

Conversion factor: ton/acre x 2.24 = MT/ha
1.0 bu/acre = 62½ kg/ha

**Data from Ridgetown College of Agricultural Technology*

Source of Organic Matter

Manure supplies about 500 pounds of dry matter per ton in a form that is easily decomposed by microorganisms. Manure when applied to a soil:

- increases activity of the microorganisms
- improves the physical condition of soils
- increases the water-holding capacity of soils and promotes the infiltration of rainfall
- improves soil fertility

The amount of humus that accumulates with the decomposition of crop residues generally follows the level of soil nitrogen. The crop residues have a wide carbon to nitrogen ratio that is narrowed by adding nitrogen usually in a chemical form. Manure does not require supplemental nitrogen to assist the decomposition processes. The principal exception would be with manures containing large amounts of bedding material, such as horse manures.

Table 17. Content and market value of plant nutrients in different manures

Source	Plant nutrient (lb/ton)			Value per ton*
	Nitrogen (N)	Phosphorus (P)	Potassium (K)	
Horse	13	2	10	5.39
Cow	11	1	12	4.52
Hog	15	5	8	7.40
Sheep	18	3	16	7.81
Poultry (Broilers)	33	18	14	19.91

Conversion Factor: lb/ton x 0.5 = kg/MT
Value per ton x 0.9 = value per MT

**Value of nutrients: Nitrogen 25¢, Phosphorus 57¢ and Potassium 10¢ per pound*

When and Where Used

There is relatively little data available that details the fertility value of manures when applied during different seasons of the year. This is particularly true where the operation involves the production of manures as liquids or slurries. The fertility value of manure is determined largely by:

- the availability of land to use the manure
- the crop or crop sequence used on a farm
- the season when manures may be applied
- the value of the manure as determined by kind of livestock or poultry, nutrient losses due to handling, storage and application

It has been estimated that the plant-nutrient value of manure is equivalent to chemical fertilizers when the manure is applied in the spring.[1] In Ontario, it is not possible to spread manure from mid-June to mid-October on land used for corn production. This means that manure available for spreading during this period is of no value for corn production, and other areas of crops must be used for disposal purposes. Manure applied in fall could lose 50% of its value as a nitrogen source, since under winter conditions the loss of nutrients in manures will be high due largely to losses of nitrogen to the atmosphere, run off and erosion.

In general, manure should be applied for the crops with the highest acre value. Vegetable crops usually pay a higher return than field crops. Of the field crops, corn gives high returns from 10 to 20 tons of manure per acre. In clean-cultivated orchards, on small fruit plantations, and for vegetable crops, manure should be applied in fairly heavy amounts (10 to 20 tons per acre). Here the intensive cultivation and cropping deplete the organic matter in the soil at a rapid rate.

Storage and Handling of Solid Manure

Most farm animals use only a small part of the nitrogen, phosphorus, and potassium contained in their feed. About 70% of the nitrogen, 85% of the phosphorus, and 90% of the potassium in the feed is excreted in the manure. Between 40 and 75% of the plant-nutrient value of manure is in the liquid portion.

Losses of plant nutrients from manure occur in the following ways:

- leakage of the liquid through broken stable floors
- soaking into barnyards and feedlots
- leaching when improperly piled in the open
- not using sufficient bedding
- heating in the pile
- erosion when spread on sloping and frozen ground
- rapid drying when spread on the surface of the soil during warm, dry weather

It has been estimated that about 25 to 30% of the potential value of manure is being realized. None of these losses can be avoided entirely, but they can be reduced by careful handling. Adequate amounts of bedding or litter should be used to absorb the valuable liquid portion of the manure. Cereal straw is the usual bedding material; its absorption capacity is increased by cutting. Wood shavings and sawdust are also satisfactory. Although it is not used extensively, peat moss is one of the best litter materials because it absorbs 10 times its weight in liquid; cereal straw will hold two to three times its weight.

If manure is spread and left on soil surface each day, 30 to 50% of nitrogen may be lost through freezing or drying in the field. Rapidly melting snow will carry nitrogen and potassium from rolling land.

If manure is stored in the open, the pile should be well compacted and located where it will receive neither roof water nor surface water from higher land nearby. In covered feedlots or pens, manure can be allowed to build up for several months which is an ideal way to store manure. The manure is protected from rainwater and is tightly packed. Plenty of bedding should be used to absorb the liquid. One important advantage of storing manure is that it can be spread when it is possible to plow it under almost immediately, and thus avoid nitrogen losses during drying. Well-rotted manure has a better balance of nitrogen, phosphorus, and potassium than fresh manure, and pound for pound rotted manure contains a higher percentage of available plant nutrients than fresh manure. For farm use, it is not economical to rot manure in order to get a more concentrated fertilizing material.

Liquid or Slurry Manures

Since 1960 the production of livestock and poultry in Ontario has tended to develop in high-density confinement facilities (Figure 35). In a free stall dairy barn with slatted floors and a liquid manure system, each cow has about 100 square feet of floor space; a similar pole-barn for beef rearing provides 20 square feet per animal; a finishing barn for hogs allows about 6 square feet; poultry (broiler) less than one square foot, and up to four leghorn layers may occupy a wire cage with a floor space 12 by 18 inches.

With the confinement facilities the handling of animal manures is a major management problem. This section outlines several aspects of handling the manures as a liquid or slurry.

Some advantages of a liquid manure system are:

- low labor cost for collection, storage and handling
- possible opportunities for better sanitation practices
- a method of lowering the cost of production

Each confinement operation has a special problem in handling the animal manure. With liquid systems the manure accumulates or is deposited in a retaining structure such as a concrete facility or an open lagoon by one or more of the following:

- scraping a yard or pen with a tractor-mounted blade
- a conveyor system in gutters
- depositing directly in channels under slatted floors
- washing the pen, yard or gutter with pressure hoses

Manure Storage

In Ontario, animal wastes particularly from a liquid handling system should not be spread on land during the winter season. Early spring spreading on frozen or snow-covered land is discouraged to avoid runoff and possible stream pollution. Consequently, manures have to be stored

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1 *McKenna, M.F. and J.H. Clark. 1970. The economics of storing, handling and spreading liquid hog manure for confined feeder hog enterprises. Department of Agricultural Economics, University of Guelph, Guelph, Ontario.*

for up to six months of the year. With liquid handling systems the common storage facilities are concrete structures under the rearing area, or part of the structure inside and part outside or entirely outside. Earthen structures lined and unlined are also used.

Anaerobic storage – Anaerobic processes occur in an environment free of oxygen. Anaerobic and facultative bacteria that occur in animal wastes multiply rapidly and convert organic solids to liquids and gases. Under suitable environmental conditions of pH and temperature the anaerobic process is usually described as a two-step operation:

The acid-forming stage involves the liquefaction of many insoluble compounds. Lignins are largely unchanged in the anaerobic process of decomposition. The net result of organic degradation during this phase is to convert many insoluble compounds into soluble intermediate products. Organic acids are produced and if the pH drops much below 6.5 further digestion becomes restricted.

To keep the anaerobic process operational, the intermediate products produced by the acid-forming stage are converted to end products. The amino acids are converted to ammonium compounds. The sulfur-containing amino acids yield hydrogen sulfide and mercaptans as a portion of the end product. The methane forming bacteria convert certain acids and alcohols to methane and carbon dioxide. The activity of the methane bacteria tend to prevent a buildup of acids within the system.

For the anaerobic digestion process to operate properly, it is necessary to have a temperature around 20°C and as the temperature rises above 20°C, less time is required for digestion of the waste. Because of the temperature factor, the anaerobic process virtually ceases during the winter months.

Anaerobic storage facilities should not be constructed without advice from qualified personnel. In determining the location of an anaerobic lagoon consideration should be given to:

- wind direction
- area far removed from residences to avoid complaints about sights, odors and hazards
- provision for the control of surface drainage to avoid runoff entering the storage
- location in an impervious subsoil or plan on installing an impervious liner
- access to adequate acreages of land to spread the effluent

Aerobic storage – Dilute mixtures of animal manures are biodegradable when dissolved oxygen is readily available. Under aerobic conditions and with heat and sunlight, the bacteria decompose the manure releasing carbon dioxide which supports the growth of algae. Treatment of animal manures in aerobic storage facilities oxidizes some of the ammonia nitrogen to the nitrate form (Figure 36). Some ammonia nitrogen is lost by volatilization to the atmosphere.

The effluent from an aerobic storage contains most of the nutrients found in the raw manure as well as organic material that cannot be oxidized by the bacteria common to the storage facility. The concentrations of nitrogen, phosphorus and organics are such that the effluents cannot be discharged to bodies of fresh water. The effluents and sludge should be disposed of by land application.

The advantages of treating animal wastes in aerobic storages or oxidation ditches are:

- the odor problem is minimal, so long as a supply of dissolved oxygen is maintained.
- the effluents from aerobic storages can be held until spread on land.

Figure 36. A surface aerator incorporates oxygen with liquid manure in a storage facility.

Quantities and Composition

The quantity and composition of manures from various livestock and poultry may be approximated from the data in Table 14. If the manure is handled as a liquid, additional water is usually added. Manures at 85% moisture content or greater will normally flow by gravity in deep gutters, and at 95% moisture or greater it can be pumped.

The plant nutrient content of liquid manures will vary because of:

- kind, age, weight and purpose of animal or poultry
- method of storage whether in anaerobic or aerobic lagoons
- duration of storage
- dilution of waste by rainfall or by intentionally adding water

The data in Table 19 indicate the approximate quantities of nitrogen, phosphorus and potassium in liquid manures from cattle, hogs, and poultry. The rates of application are volumes required to apply approximately 100 lb nitrogen per acre (112 kg nitrogen per ha).

Table 19. The approximate nutrient content of liquid manures for selected rates of application

Source	Gal/acre	Nutrient (lb)		
		Nitrogen N	Phosphorus P	Potassium K
Cattle	5,000	100	22	83
Hog	3,000	100	26	33
Poultry	1,500	90	40	29

Conversion factors: 1.0 gal/acre = 11.2 litre/ha
1.0 lb = 0.45 kg

Gas and Odor Problems

Gases are a natural end product of the biological decomposition of liquid or semi-solid manures. The inorganic gases are primarily hydrogen sulfide, ammonia, carbon dioxide, nitrogen, oxygen and hydrogen. Hydrogen sulfide

and ammonia are malodorous gases. Gases of an organic nature such as methane, and a group of gases arising from the anaerobic decomposition of compounds containing nitrogen and sulfur (mercaptans, indoles) and groups of organic acids, aldhydes, ketones and other compounds are produced.

There are several sources of obnoxious odors associated with livestock- or poultry-rearing operations. At times and with certain activities on a farm, the odor level may become great enough to cause complaints or legal action from the neighbors. The principal sources of odors are:

- from the barn or rearing area
- from outdoor feedlots or confinement facilities
- when spreading the manure on land
- when disturbing the waste for loading or cleaning up
- from overloaded aerobic treatment facilities
- from anaerobic storage lagoons on warm days with high humidity, and during the spring turnover of the lagoon

Perhaps the most common odor-causing compound is hydrogen sulfide – the odor associated with rotten eggs. The gas results from the anaerobic decomposition of sulfur-containing materials such as proteins and organic matter.

Besides being a nuisance some gases in sufficient concentrations can be toxic, cause asphyxiation by displacement of oxygen or can be explosive. These gases can accumulate in covered liquid-manure storages or be released from open storage inside the barn, particularly during agitation. For instance, hydrogen sulfide is readily released and most dangerous within the first few minutes after agitation. Hence, maximum ventilation must be provided and exposure of humans and animals to this gas must be avoided. In high concentrations, hydrogen sulfide rapidly dulls the sense of smell and odor detection. Several deaths attributed to this gas have occurred. Smoking or use of an open flame should also be avoided because methane in critical proportions with air can be explosive.[1]

Agricultural Code of Practice

An *Agricultural Code of Practice* has been prepared to guide persons proposing to build new buildings or remodel existing buildings. It is available from Ontario Ministry of Agriculture and Food, Ministry of Environment and Ministry of Housing.

The purpose of the *Agricultural Code of Practice* is to assist farmers in reducing the potential of their livestock operation to pollute air, soil and water and to provide guidelines for the rational use of land in relation to the livestock industry.

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1 *Canada Animal Waste Management Guide. 1972. Engineering Service, Agriculture Canada, Ottawa.*

LAND FOR WASTE WATER DISPOSAL

Waste waters which are disposed of on land are primarily from industries processing agricultural products, effluents from urban sewage treatment facilities and from very few industries. With disposal as the primary objective, water applied to land may be low in the concentration of plant nutrients and the volume of water will be in excess of normal plant requirements.

Characteristics of Waste Waters

Several wastes are listed with brief descriptive notes about the characteristics of the wastes that may be important in considering land disposal.

Cannery Wastes

- waste water from washing, processing and canning
- large volumes
- seasonal in nature
- low nutrient content and low organic matter, some exceptions

Potato Processing

- from the initial washing of potatoes and from processes to produce fries, chips, flakes and other products
- high volume and high in organics (starch)
- low plant nutrient content
- pH may reach 12 if lye peeling is used

Milk and Cheese Plants

- large volume of waste water from washing operations, plant cleanups and sanitizing procedures
- whey applied to land provides about 3 lb nitrogen, 0.75 lb phosphorus and 3.5 lb potassium per ton liquid waste (200 gallons) (1.5 kg nitrogen, 0.4 kg phosphorus and 1.8 kg potassium per metric ton of liquid waste)

Poultry Processing

- 5 to 10 gallons (20 to 40 litres) of process water per bird
- processing may involve 50,000 birds per day
- high volume, low nutrients, low organic matter content

Domestic Sewage

The partial treatment of domestic sewage is accomplished by biological action in stabilization ponds or lagoons. Such facilities are used by some Ontario communities that do not have treatment plants or septic tanks, and where weeping tiles are not available. The general design characteristics of lagoons are about 1.0 acre (0.5 hectares) of water surface per 100 people and a water depth of 3 to 5 feet (1 to 1.5 metres). Normally, the overflow from a lagoon goes to a stream but some communities apply the effluent to farmland, usually hay or pasture. The effluent is low in essential plant nutrients, total nitrogen (10 ppm), phosphorus (4 ppm) and potassium (10 ppm). As the effluent could contain all the bacteria and viruses normally associated with human waste, it is not applied to crops consumed directly or eaten uncooked by people such as, lettuce, radishes, carrots and tomatoes.

Septic Tanks and Weeping Tiles Beds

Domestic sewage from dwellings is partially treated by holding in a septic tank and allowing the tank effluent to drain into underground weeping tiles. Renovation of the waste is accomplished by soil microorganisms in an aerobic environment and by the adsorption of phosphates by soil colloids. For proper renovation to occur, it is essential that the effluent be introduced into 5 to 6 feet (1.5 to 2 metres) of well-drained and moderately permeable soil. Coarse sands, gravels and impermeable clays are not suitable soil textures for renovating septic tank effluents. More details regarding the construction, size and location of septic tank systems are available from various health authorities and departments.

Other Wastes

There are other sources of wastes and waste waters, primarily industrial, that may be applied to the land and which require careful evaluation of the waste characteristics. Tannery wastes are quite variable in solids, pH, organics and metal content. Normally, laundry wastes are high in phosphates, various washing compounds and may contain caustic compounds. Wastes from metal-finishing plants may yield metals that are toxic to vegetation. Spent alkalis and acids are special problems when land disposal is considered.

Normally plans, specifications and various details must be filed with the Ministries of Health or Environment before land may be used extensively for waste water disposal.

Site Characteristics for Waste Disposal

When wastes or waste waters are applied to land, there are four sinks or final places where the waste or its by-products may end. These are:

1. to the atmosphere by volatilization: ammonia losses from manures and the release of carbon dioxide from the decomposition of organic residues
2. retained in the soil as non-decomposable residues, e.g. organics that virtually resist biodegradation and various ions or elements held on the soil exchange sites (Ca^{++}, NH_4^+, Na^+, etc), or ions chemically fixed
3. to the groundwater, for example the mobile compounds nitrate and chloride
4. removed from the soil by plant utilization, erosion, and runoff.

The primary use of land is for the production of food and feed for humans and livestock. If land disposal is shown to be feasible and to involve minimal hazards primarily to health, a major problem could be the finding of suitable sites. The principal features to be considered in assessing the suitability of a site for waste disposal are summarized below.

Groundwater

Groundwater is one of our most valuable resources. When the land surface is used for waste disposal, there is a real or potential hazard for groundwater contamination. The need to reduce or prevent contamination is obvious. To eliminate all groundwater contamination is not economically feasible. A major objective in using land for waste disposal should be to minimize health risks and hazards while maintaining disposal costs within reasonable limits.

The source or point at which waste water enters the soil surface may be a few square feet or several acres in size. The waste water passes through a zone that is unsaturated and well aerated (aerobic). As the added water reaches the water table, it tends to flare out in a lateral movement giving rise to what is often termed the mounding of the groundwater. These mounds resulting from recharging activities may have a base covering several acres and be many feet in height. As the mound increases there is a tendency for the water to move horizontally to natural discharge points or to places (wells) where the groundwater is removed for some particular use.

Groundwater moves from an area of high pressure to one of lower pressure and the volume that moves is dependent on the pressure differential and the permeability of the material through which it flows. It is not unusual to find that groundwater or excessive additions of waste water move in a direction opposite to the slope of the land surface. Discharge points such as wells may not be contaminated by waste water even though they are located near the recharge area so long as the direction of flow is away from the well. On the other hand water supplies often miles away from the recharge area may be affected or contaminated.

Bedrock

The depth to bedrock is an important consideration in selecting a site for waste disposal. If the bedrock occurs 2 feet (0.5 metre) below the soil surface, the volume of aerobic soil is materially reduced when compared with 6 or more feet (2 metres) of soil. The dip or tilt of the bedrock is an important feature affecting the volume and direction of flow of the groundwater. Furthermore, some bedrock is highly fractured and permits the downward movement of added water; other bedrock is relatively porous or consists of seams or layers of permeable material which transmit water.

Natural Soil Drainage

When potential contaminants are applied to land, the principal process to degrade the waste and renovate the waste water involves the action of naturally occurring soil microorganisms in an aerobic environment. A deep well-drained soil, would normally provide a near-ideal environment for the biodegradation of wastes and the various processes that chemically or biologically fix and immobilize several elements and compounds.

If anaerobic conditions occur in a soil, either naturally or by flooding, the results include less oxidation of the organics, the development of foul odors, changes in the solubility and mobility of various chemicals, and a tendency for a reduction in soil permeability due to the clogging of soil pores.

Soil Permeability and Texture

For liquid wastes to be degraded by a soil, it is essential that the liquid enter the soil (infiltration) and that the renovated water move through the soil profile (percolation) to augment the groundwater supply. As already mentioned it is necessary that a waste be retained in a soil for a period of time to accomplish the biological degradation and adsorption of some compounds. Obviously, the highly permeable coarse sands and gravels permit the waste to pass through without renovation, and such soil materials may not contain a supply of colloidal material to facilitate chemical reactions. When waste waters are applied to soils with very low infiltration and percolation rates, the waste tends to flood the soil surface leading to anaerobic conditions and possible runoff and erosion.

Soil Slope

Ideally, wastes are applied to lands that are nearly level or on a gentle slope (less than 5%). This precaution is necessary to avoid runoff and erosion and to give the waste time to infiltrate the immediate soil surface. Normally, waste waters are applied to land with a vegetative cover, primarily hay, pasture or woodlots. A dense cover of vegetation retards the overland flow of water, increases infiltration, improves percolation and transpires large volumes of water. The application of livestock manures, sewage sludges or waste waters should not be made on a snow-covered or frozen sloping land.

Waste Application

In Ontario, most waste waters are disposed of by overhead irrigation systems. Other methods used to a limited extent and generally in special cases include an overland flow or spreading technique and discharging the waste waters into specially prepared furrows or ditches.

The design, kind of equipment and field layout of irrigation systems require technical advice from specialists. From the soil aspect, consideration must be given to: rate of application (in./hr), and the amount applied at a given time (inches, and time of application).

Obviously, in overhead irrigation with sprinkler systems the rate of applying the waste must not exceed the infiltration rate for the particular soil. On well-drained fine sand or loam textured soils, waste waters are usually applied at rates not exceeding 0.25 inches (0.6 centimetres) per hour; on fine-textured silt loams and clay loams the maximum rate of application would be 0.1 to 0.2 inches (0.2 to 0.5 centimetres) per hour.

The amount of waste water (usually inches over unit area) that should be applied at any one time of irrigation cannot be predetermined. The amount that may be applied depends on:

a. the period in the growing season, lower amounts early in the season and increasing amounts as the vegetation grows
b. the moisture-holding capacity of a soil, low amounts on sandy soils and larger amounts on permeable loams and fine-textured soils

c. the antecedent soil moisture status, irrigation must be withheld if the natural precipitation has contributed to a soil that is at or near maximum moisture-holding capacity.

As an approximation, sandy loam and loam soils have been irrigated with 2 inches (5 centimetres) of waste water per week plus natural rainfall, but for slowly permeable clay loams and clays the weekly application should not exceed 1 to 1.5 inches (2.5 to 4.0 centimetres) including precipitation. Each site and soil used for waste water disposal should be evaluated individually.

WASTES FROM SEWAGE TREATMENT PLANTS

Land disposal of waste waters and sludges from municipal treatment plant is not a new idea; it has been practiced in European and Asian countries for centuries. Recently, though a concern about the damage to our soil, air and water resources has arisen, if the practice is not monitored for kinds of materials added and controlled with respect to disposal site and frequency of application.

Sources and Kinds of Wastes

Urban areas with a sewer system for the collection and transport of domestic, commercial and industrial wastes provide a variety of treatment processes at a sewage treatment plant, also referred to as water pollution control plant.

Primary Sludges

In plants with only a primary treatment, the incoming wastes are screened to remove large objects and some settling is allowed to occur to remove the stones and gravel. The waste then goes to large sedimentation tanks or clarifiers where most of the solids settle to the tank bottom. The longer a waste is held in a settling tank, the greater the accumulation of sludge. The primary sludges are usually light and fluffy and when pumped from the settling tank are very low in solids. If a flocculant such as alum, ferric compounds or calcium oxide is added more solids are removed during the settling process and the sludge is said to be more stable.

Primary sludges contain virtually all the incoming microorganisms as well as pathogenic viruses. When applied to land special considerations are necessary:

- must not come in contact with fruits or vegetables used for human consumption
- must not be applied to pasture currently being grazed by livestock
- when applied to land provision should be made for immediate incorporation with the soil

These precautionary measures are similar to those when septic tank pump-outs are applied to land and covered almost immediately.

Activated Sludges

In treatment plants with a form of forced aeration the primary sludges pass through a series of structures that have facilities to bubble air into the wastes. The extra air adds oxygen which encourages a profuse growth of organisms that degrade most of the organic material to carbon dioxide and water. This is referred to as aerobic decomposition. Provision is made to return some of the sludge from the system to the primary settling tanks. As this sludge contains the organisms that actively degrade the waste it is said to activate the process early in the system.

Activated sludges are similar to primary sludges: they may be flocculated and caution is necessary when land disposal is practiced.

Digested Sludges

Some treatment plants pump portions of the primary and activated sludges to digesters which are large cylindrical structures that retain the sludges for 20 to 30 days. Provision is made to heat the digester contents up to 35°C. The waste undergoes anaerobic decomposition, that is, no oxygen is present. The by-products include methane gas which is collected and used to heat the digesters, a variety of other gases (nitrogen compounds, hydrogen sulfide) and a sludge.

Anaerobically digested sewage sludges are gray-black in color, contain varying amounts of solids and many chemical elements (Table 20). Some communities depend on land application as the primary methods for the disposal of digested sludges. As these sludges are concentrated, they may contain chemical compounds that could contaminate soil and water or render crops unsuitable for livestock or human consumption.

Table 20. The composition of anaerobically digested sewage sludges from nine Ontario treatment plants*

Constituent	Range in Concentration
Dry matter (solids)	1.7 to 6.0 %
Total nitrogen	0.1 to 0.3 %
Total phosphorus	0.06 to 0.3 %
	Concentration in parts per million (ppm)
Ammonium nitrogen	74 to 1100
Potassium	28 to 120
Sodium	50 to 684
Calcium	850 to 9900
Magnesium	110 to 471
Aluminum	71 to 1487
Iron	122 to 5700
Zinc	7 to 537
Copper	7 to 280
Nickel	0.3 to 325
Lead	6 to 120
Manganese	4 to 77
Chromium	1 to 142
Cadmium	0.2 to 7.5
Mercury	0.06 to 1.24

Note: (a) 1.0% is equal to 10,000 parts per million (ppm) or 10,000 micrograms per litre.

(b) 1.0 inches of a liquid over one acre (1.0 acre-inches) is approximately 22,600 gallons, 226,000 pounds or 0.44 million pounds.

(c) For each centimetre of liquid applied over one hectare, the amount of element added in kg/ha is equal to the concentration of the element in ppm divided by 10.

**Progress Report, 1973. Department of Land Resource Science, University of Guelph.*

Treatment Plant Effluents

Regardless of the treatment process used by a municipality, there are almost as many gallons of effluents as there are gallons of incoming raw sewage. The effluents are normally chlorinated to kill most organisms before discharging to streams or bodies of surface water.

The effluents contain dissolved or suspended organic materials, nitrogenous and phosphorus compounds as well as traces of other chemical elements and microorganisms, some of which may be toxic. Many studies have shown that treatment plant effluents when discharged in surface waters provide an environment suitable for the growth of algae, rooted aquatics and enhance a degeneration of water quality.

Research has shown that the addition of a flocculant, which also precipitates about 90% of the soluble phosphates, improves the quality of the effluent by reducing the concentrations of phosphorus and organic material.

Virtually no sewage treatment plant effluents are used in agricultural crop production in Ontario. A limited use is made of effluents from lagoons or stabilization ponds for hay and pasture irrigation in southern Ontario, a practice which serves to reduce the pollution load on the receiving bodies or streams of water. In parts of the U.S.A. where precipitation is low, 10 to 20 inches (25 to 50 centimetres) annually, large volumes of plant effluents are used to irrigate a variety of crops.

Use of Sludges in Agriculture

The use of treated sewage sludges on crop-producing land has been practiced for two principal reasons: (1) a method of disposal for towns and cities that have farm operators prepared to accept the waste and (2) a recognition by farmers that the waste is a source of plant nutrients, especially when chemical fertilizers may be considered expensive or in short supply.

The data in Table 20 indicate the wide variation in the composition of sludges and emphasize the need for knowing what a sludge contains before applying to crop-producing land. For example, consider a sludge that contains: ammonium nitrogen 900, phosphorus 2000 and cadmium 6.0 parts per million. A land application of 0.5 inches (approximately 11000 gallons) would add: ammonium nitrogen 100, phosphorus 228 and cadmium about 1.0 pound per acre. Generally, the sludge would supply an adequate amount of readily available nitrogen for a corn crop but the phosphorus is far in excess of the crop need and the level of soil cadmium would be more than doubled.

The technical literature indicates very clearly that the intensive use of treated sludges on crop-producing land could result in:

- soil contamination by various heavy metals in the sludge (zinc, copper, nickel, cadmium and others)
- applications of excessive amounts of nitrogen and phosphorus which could contaminate the groundwater especially by nitrogen and by erosion and runoff pollute surface waters with any one or all of the elements in the sludge
- the production of food and feed for humans and livestock that are hazardous to consume because of excessive levels of elements originally in the sludge

Because of unsolved problems in the use of sewage sludge on agricultural land, the Ontario Ministries of Agriculture and Food and the Environment, have prepared guidelines for sewage sludge use on crop-producing land. The following criteria have been considered, recommended and are subject to frequent reviews.

1. In Ontario, only digested sludges are to be considered for utilization on crop-producing land. A permit or licensing system is operational for the land disposal of raw sludge wastes from septic tank pump-outs and other devices not having secondary treatment facilities
2. Sludges should not be applied to organic soils and mineral soils with a pH less than 6.5, except for the lime-treated sludges
3. Several criteria which relate to field and site conditions, such as, distance from watercourse, slope, soil permeability, frost conditions, depth to groundwater and others
4. Most suitable crops for sludge disposal are corn, grass, hay, commercial sod; land receiving sludge may not be used for six months following an application for pasturing or the production of fruit and vegetables
5. Application rates should be based on the ammonium-nitrogen content of the sludge and the crop requirement for nitrogen
6. The suitability of sludge may be determined by the use of ratios of metals to ammonium nitrogen in an attempt to avoid metal toxicity.

POOR

QUALITY

ORIGINAL